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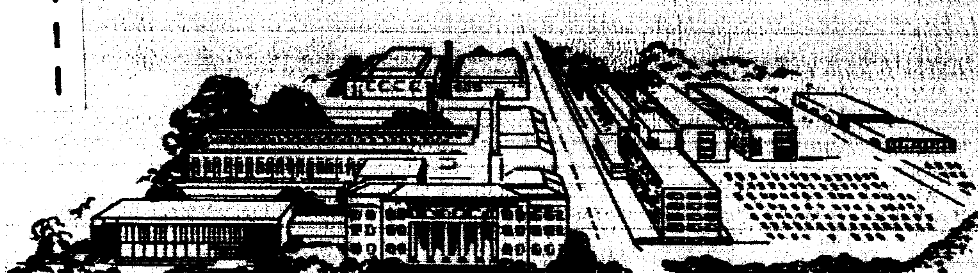

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WOOD AND FOREST PRODUCTS

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FINAL SUMMARY REPORT

on

STUDIES OF HIGH-FREQUENCY
WELDING PROCESS

to

GEORGE C. MARSHALL
SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

June 11, 1963

by

W. R. Byrne, J. J. Vagi, and D. C. Martin

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FOREWORD

Research described in this report was conducted by the following research team in the Metals Joining Division:

D. C. Martin, Division Chief
G. E. Faulkner, Assistant Division Chief
J. J. Vagi, Senior Welding Engineer
W. R. Byrne, Welding Metallurgist
R. N. Burnham, Welding Technician
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The program was initiated and conducted under the guidance of P. J. Rieppel, Associate Manager, Physics and Metallurgy Department. R. P. Meister, Research Metallurgist, and R. E. Monroe, Assistant Chief, assisted in the areas of weld evaluation and final report preparation, respectively.

This program was initiated under the technical supervision of Mr. W. G. Groth, Special Projects Office, Marshall Space Flight Center. Mr. Gordon Parks, Welding Coordinator, Marshall Space Flight Center, provided technical supervision during the final portions of the program.

Successful completion of the program was only possible through the helpful suggestions and contributions of the individuals named above.

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STUDIES OF HIGH-FREQUENCY WELDING PROCESS

by

W. R. Byrne, J. J. Vagi, and D. C. Martin

SUMMARY

As part of the NASA program of space-launch-vehicle development Battelle Memorial Institute conducted studies of the applicability of the high-frequency resistance welding process to space-launch-vehicle materials and configurations. The materials selected for study included 2014-T6, 5456-H343 and 7179-T6 aluminum alloys, AISI 301 and 310 stainless steels in the full hard condition, and titanium-6 aluminum-4 vanadium alloy. All of these materials were used in the form of 2-in.-wide strips. The studies were conducted in three phases. First, weldability and mechanical properties of selected materials were investigated. Second, information was obtained on extending the process to the fabrication of longitudinal and circumferential joints in a typical range of space-vehicle thicknesses and dimensions. Third, the information obtained in the earlier phases was evaluated and projected into tooling design configurations to establish final tooling parameters for the manufacture of space-vehicle components.

In Phase I, many welds were made and evaluated to establish satisfactory conditions for welding the selected alloys. Satisfactory welding conditions were established initially for the 2014-T6 aluminum alloy by studying the effects of the welding-process variables on weld properties. Then, the conditions that produced high joint efficiencies in the 2014-T6 alloy were adapted for use in welding the remaining alloys. High-strength welded joints were obtained with all of the materials that were welded using conditions similar to those used for welding the 2014-T6 alloy. The highest joint efficiencies obtained were in the range of from 76 to 100 per cent depending on the material as shown in the following tabulation.

Material	Thickness, in.	Ultimate Tensile Strength, ksi	Joint Efficiency, per cent
AA2014-T6	0.068	61.2	87
AA7179-T6	0.062	60.3	76
AISI 301 (full hard)	0.072	166.2	87
AISI 310 (full hard)	0.072	127.1	93
	0.114	122.0	89
Ti-6Al-4V	0.063	137.3	100

Demonstration that such joint efficiencies could be obtained in heat-treatable alloys such as 2014-T6 without any post-weld treatment, and in strain-hardened alloys such as AISI 301 was a major program accomplishment. The joint efficiency of butt weldments in these alloys made by other welding processes used in fabricating space-launch vehicles is always much lower than it was found possible to achieve by high-frequency resistance welding. Even better joint efficiencies in high-frequency resistance welds are expected with some of these materials when welding-process parameters are optimized.

In Phase II, evaluation of the welding results obtained during the initial phase of the study showed that weldments having high joint efficiency were obtained with the stainless steels using a relatively wide range of welding conditions. High joint efficiencies also were obtained with the 2014-T6 and 7179-T6 aluminum alloys. The range of welding conditions required to produce good welds was more limited with the aluminum alloys, a characteristic common to many welding

processes. The titanium alloy weldments had high joint efficiency but exhibited some evidence of embrittlement. Properties of the titanium welds may have been affected by interstitial contamination, despite the precautions taken to avoid this. On the basis of weldability and mechanical properties the stainless steels were selected as the most readily adaptable alloys to the high-frequency resistance welding process. Strength data from weldments prepared in 0.072- and 0.114-in.-thick stainless steel strips show that variations in joint efficiency with thickness were not appreciable. On the basis of the information obtained from this study, thicknesses required to support specified loads of 4000 lb minimum and 16000 lb maximum per inch of weld are tabulated below:

Material	Required Load Per Inch of Joint, lb	Yield Strength of Weldment, ksi	Thickness Required, in.
AA2014-T6	4000	46.6	0.086
	16000		0.340
AA7179-T6	4000	53.9	0.075
	16000		0.300
AISI 301 (full hard)	4000	104.0	0.037
	16000		0.150
AISI 310 (full hard)	4000	92.5	0.043
	16000		0.170
Ti-6Al-4V	4000	94.0	0.043
	16000		0.170

It is likely that higher strength welds can be produced with the process when optimium welding conditions are developed, and the thickness to support the required loads would be decreased.

In Phase III, tooling design concepts were developed as required to establish final tooling parameters for production systems utilizing the process for the manufacturing of space-vehicle components. Special tooling design concepts were developed for fabricating T-sections and attaching them to tankage walls as stiffeners. In some applications, stiffener sections are machined at great expense from heat-treated or cold-worked solid slabs. Much of the original material is removed during machining and scrapped. Conventional welding processes are not used for fabricating the stiffened sections because of losses in strength of the base metal due to the heat of welding. On the basis of the studies made it should be possible to produce such components with high-frequency welds having high joint efficiency combined with narrow heat-affected zones at a significant cost savings.

The information developed on this program indicates that

(1) High-frequency resistance welding is applicable to space-launch-vehicle materials. As-welded joints made by this process exhibit exceptionally good joint efficiency.

(2) The process is adaptable to thicknesses and configurations required in launch vehicles.

(3) Tooling configurations required to establish final parameters for a production system useful in the fabrication of launch vehicles can be developed.

(4) Additional research should be conducted to extend the application of high-frequency resistance welding in areas where significant cost savings could be made in launch-vehicle fabrication.

INTRODUCTION

A major requirement in space-launch vehicles is the need for lightweight structures to obtain maximum performance from the propulsion system. These lightweight structures are achieved through the use of heat-treated and work-hardened alloys. Fabrication methods that minimize loss of base-metal strength are desirable to take full advantage of the strength of the alloys.

High-frequency resistance welding is considered promising as a joining method for space-launch-vehicle alloys because the loss of base-metal strength is expected to be minimized. The weld heat-affected zones of high-frequency resistance welds are very narrow. These narrow-weld heat-affected zones minimize the effects of the weld thermal cycle on the mechanical properties of the alloys. Welds made with conventional welding processes have wide heat-affected zones in which the strengthening effects of cold working or prewelding heat treatment of the alloy are reduced or completely eliminated. Butt welds made with conventional processes often have strengths comparable to, or only slightly better than those of the annealed or partially annealed parent alloy.

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The research described in this report was undertaken because no information was available on how the high-frequency welding process would work for the unusual applications and with the materials being used or studied for present and future applications of interest to the National Aeronautics and Space Administration. To obtain the needed information on the high-frequency welding process, the research was divided into three phases. Phase I was to study and develop the degree of applicability of the high-frequency welding process to space-launch-vehicle materials. Phase II was to study and develop the adaptability of the process, including necessary power frequencies and travel speeds, to the material thicknesses and configurations required for launch vehicles. Phase III was to design tooling configurations as required for the establishment of final tooling parameters for a production system.

Each of these program phases is the subject of a subsequent major section of this report. These sections are preceded by additional introductory discussions of the following:

(1) Process characteristics

(2) Equipment

(3) Materials

(4) Experimental procedures.

Author

The introductory sections are included primarily for those readers not familiar with the details of the high-frequency welding process.

PROCESS CHARACTERISTICS

The high-frequency resistance welding process has a number of characteristics that are considered important in preparing high-strength joints in space-launch-vehicle materials and configurations. One characteristic of the process is that welds with very narrow heat-affected zones can be produced. The welding current tends to flow only near the surface of the material because of the skin effect obtained through the use of high-frequency welding current (450 kc). The heat for welding, therefore, is developed in a small concentrated volume of metal along the edges to be joined. A narrow weld zone is desirable because it produces a stronger weld than the wider zone produced by presently used welding processes. The metal that becomes molten during welding is squeezed out of the joint during the upsetting or forging portion of the cycle and no cast structure is present in a properly made weld. Consequently, the presence of low-melting phases, which contribute to cracking when trapped in the weld joint, is minimized. With some materials, the narrow heat-affected zones, and absence of cast structure may eliminate the need for postheat treatments to improve the metallurgical characteristics of weld metals.

A variety of materials including aluminum alloys, ferrous alloys, and reactive metals can be welded in a great variety of thicknesses. This versatility for joining many materials lends itself well to operations where materials are changed during production. For many difficult-to-weld materials the need for special filler-metal development is eliminated. Only the parent metal is used for making the weld. Reinforcement of the weld joint can be provided if desired. A forging action is used to bring the edges into intimate contact and complete the weld. The forging action upsets and thickens the edges being joined. The amount of reinforcement is controlled by the welding conditions and by the weld-trimming operations.

For butt-seam welding with the vee method of high-frequency resistance welding*, the edges of the strips are brought together to form a vee as shown in Figure 1. At the electrical contacts, the strips are separated. The application of high-frequency voltage across the contacts causes the high-frequency current to flow from one contact to the vee apex and back to the other contact and thus heats the edges. After the edge material reaches the proper temperature, the edges are forged together at the apex of the vee to force the two edges into intimate contact to complete the weld. The forging action also squeezes molten metal from the joint. Surface contamination that may be present on the surfaces of the edges is carried out of the weld joint with the molten metal. The extrusion of the molten material from the weld joint helps produce welds that are free from oxides, dirt, and other contaminants.

The control of vee-butt-seam high-frequency resistance welding is highly dependent on the configuration of the vee. Thus, it is very important to establish a consistent terminology to describe the vee configuration and to understand the effects of changes in this configuration. The nomenclature of the vee in the horizontal plane is given in Figure 2. The vee is defined in this position by

(1) The width of the vee (or strip separation), w, at the downstream, inside tip of the contact shoes, and

*The "vee method" of butt-seam welding was used exclusively in this program. Other methods used with this process are termed "in line" and "vee lap".

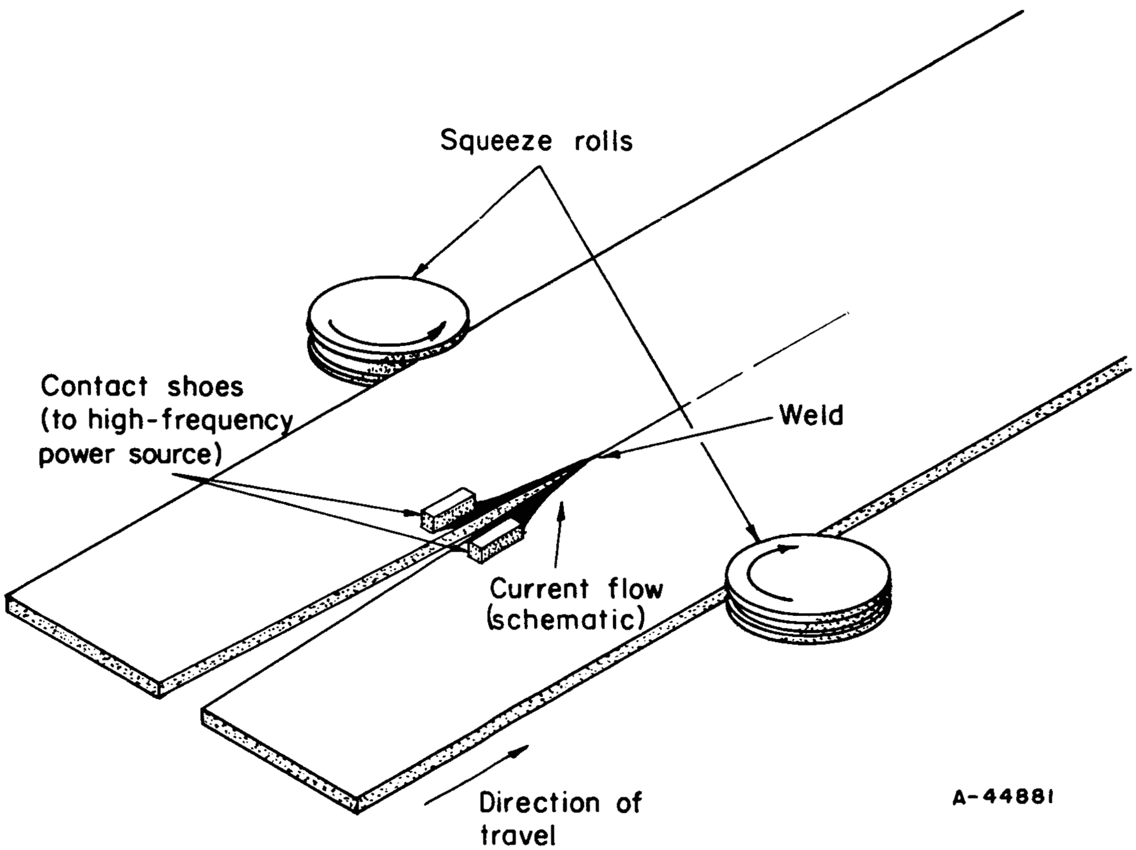
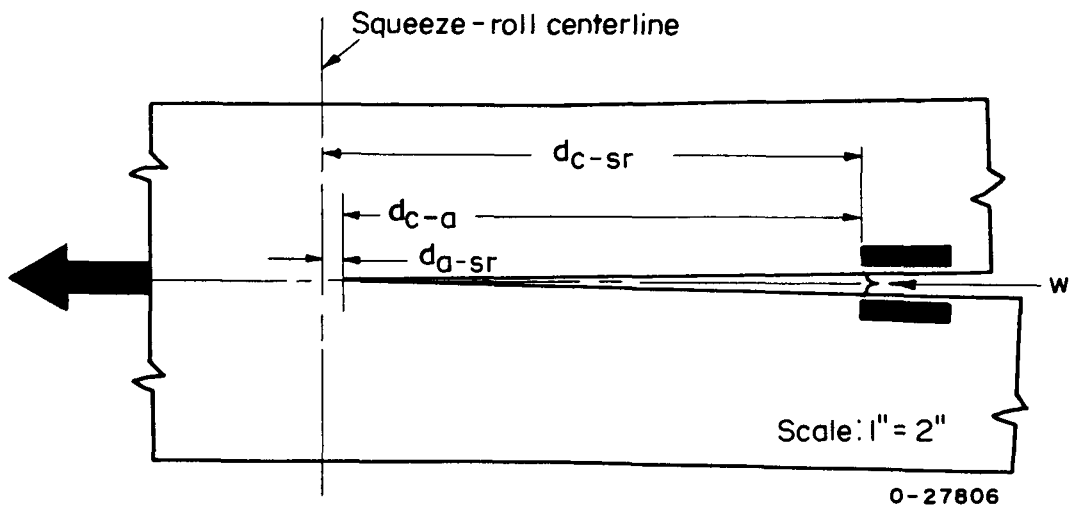


FIGURE 1. HIGH-FREQUENCY RESISTANCE WELDING OF STRIP



w = Width of the vee or strip separation at the contacts

d_{c-a} = Contact to apex distance

d_{c-sr} = Contact to squeeze-roll centerline distance

d_{a-sr} = Apex to squeeze-roll centerline distance

FIGURE 2. NOMENCLATURE OF THE VEE

(2) The contact-to-squeeze roll centerline distance, d_{C-Sr}, measured from the downstream, inside tip of the contact shoes to the centerline of the squeeze rolls.

For vees which are formed by twisting the strips, the angle of twist of each strip also is used in describing the vee. This angle was measured both at the primary guide and the electrical contacts. For vees which are formed by changing the strip elevation, the change in elevation of each strip above or below the strip centerline at the squeeze rolls is descriptive.

Current distribution within the materials and near the edges to be welded is extremely important to successful high-frequency resistance welding. To produce narrow welds and weld heat-affected zones, the depth of heat penetration must be limited. Consequently, the current path must be limited to the surface regions. The depth of heating obtained with high frequency is limited by two effects: (1) the skin effect, and (2) the proximity effect. Skin effect is the term applied to the crowding of alternating electrical current toward the surface of a conductor. For cylindrical materials that are good conductors of electricity, Brown* defines the skin thickness, s, as the depth of material through which 63 per cent of the current flows by the equation:

$$s = \frac{1}{2\pi}(10^{-9}\mu_r \sigma f)^{-0.5} ,$$

where

s = skin thickness in centimeters

μ_r = relative permeability

σ = conductivity in mhos per centimeter

f = frequency in cycles per second.

The proximity effect is that effect whereby electrical current flowing in a conductor is attracted to a nearby return conductor. In high-frequency welding the two conductors are the opposite sides of the vee. The proximity effect draws the current paths closer to each other. The result is that the current density near the edges of the strip is increased. The current density can be increased by reducing the spacing between the conductors so as to increase the proximity effect. The separation between the sides of the vee decreases as the vee apex is approached, thus the proximity effect increases, and the current density at the edges increases.

For best welding results, the top and bottom edges of the vee should be equally spaced as they approach the squeeze point. When these edges are not equally spaced, nonuniform heating occurs. More heating occurs in the closest portions of the edges due to the proximity effect.

Maximum usage of the proximity effect is limited in high-frequency resistance welding because the strip separation must be sufficient to prevent arcing across the vee. Arcing across the vee is undesirable because it causes nonuniform heating of the strip edges. The tendency for arcing to occur and the strip separation required to prevent arcing varies with the welding conditions.

*Brown, G. H., Hoyler, C. N., and Bierwirth, R. A., Theory and Applications of Radio Frequency Heating, D. Van Nostrand Company, Inc., New York (1957), pp 72-90.

Variation in the separation and length of the vee during welding will cause corresponding variations in the amount of power drawn from the generator and in the heat developed at the strip edges. Variation in the width of the vee while welding changes the distribution of current at the edges of the strips and causes changes in the depth of heating and the final surface temperature of the edges. To produce consistent welds, the width of the vee and the contact-to-vee apex distance must not fluctuate.

EQUIPMENT

The High-Frequency Resistance Welding Facility at Battelle consists of a 280-kw Thermatool High-Frequency (450 kc) welding power supply, a drive system, a welding station, guides, instrumentation, and other special equipment required to study relationships among material and process variables. The strip welding equipment and the power supply is shown in Figure 3. A floor plan of the facility is shown in Figure 4. To reduce material, tooling, and welding costs, the facility is designed for welding strip. At present 2-inch-wide strip can be welded. The mill also can be adapted to the welding of tubing or special shapes, such as tees and H's and other shapes through modifications in the tooling, guides, and rolls. Power supplies of the size used in this facility are used in pipe production to weld steel pipe with up to 1/2-in. wall thickness, 36 in. in diameter.

The power supply consists of a switchgear cubicle, voltage-control unit, rectifier assembly, oscillator cubicle, control console, high-frequency transformer, and secondary leads. These items are located as shown in Figure 4. The incoming power passes through the switchgear, a voltage-control unit, and the rectifier transformer before it enters the rectifier. A control in the switchgear permits the rectifier transformer primary to be connected in wye or delta. The secondary of the transformer is connected in wye and feeds directly into the rectifier. A wye primary connected to the wye secondary gives a low power range which is adjustable between 18 and 30 per cent of maximum power. Connecting the transformer in delta gives a high power range, which is adjustable between 30 and 100 per cent of maximum power. After leaving the rectifier transformer the power is rectified and is then fed into the plate circuit of the oscillator tubes to produce high-frequency power. The high-frequency power travels from the oscillator to a high-frequency transformer, which steps down the voltage, and then to the materials to be welded. The power supply is capable of delivering up to 280 kw of power at 450 kc to the materials being welded.

With the primary of the rectifier transformer connected either in wye or delta, the power is regulated by varying the primary voltage of the rectifier transformer between limits of 325 and 545 volts by the voltage-control unit. The primary voltage, also called input voltage, of the rectifier transformer regulates the power by controlling the value of the d-c voltage supplied to the plate circuit of the oscillator tubes. For a given set of conditions the output power varies with the square of the plate voltage. The facility includes a roll-forming mill base upon which are mounted two pullout roll stands that are driven by a 75-hp motor-hydraulic drive unit. The pullout rolls are capable of pulling strips through the welding stations at speeds in the range from 20 to 380 fpm. With this hydraulic drive unit, the strips can be accelerated from 0 to 380 fpm in 3/4 of a second. The welding station tooling is mounted on the mill base. The welding station consists of an aligning unit to align the edges of the strips

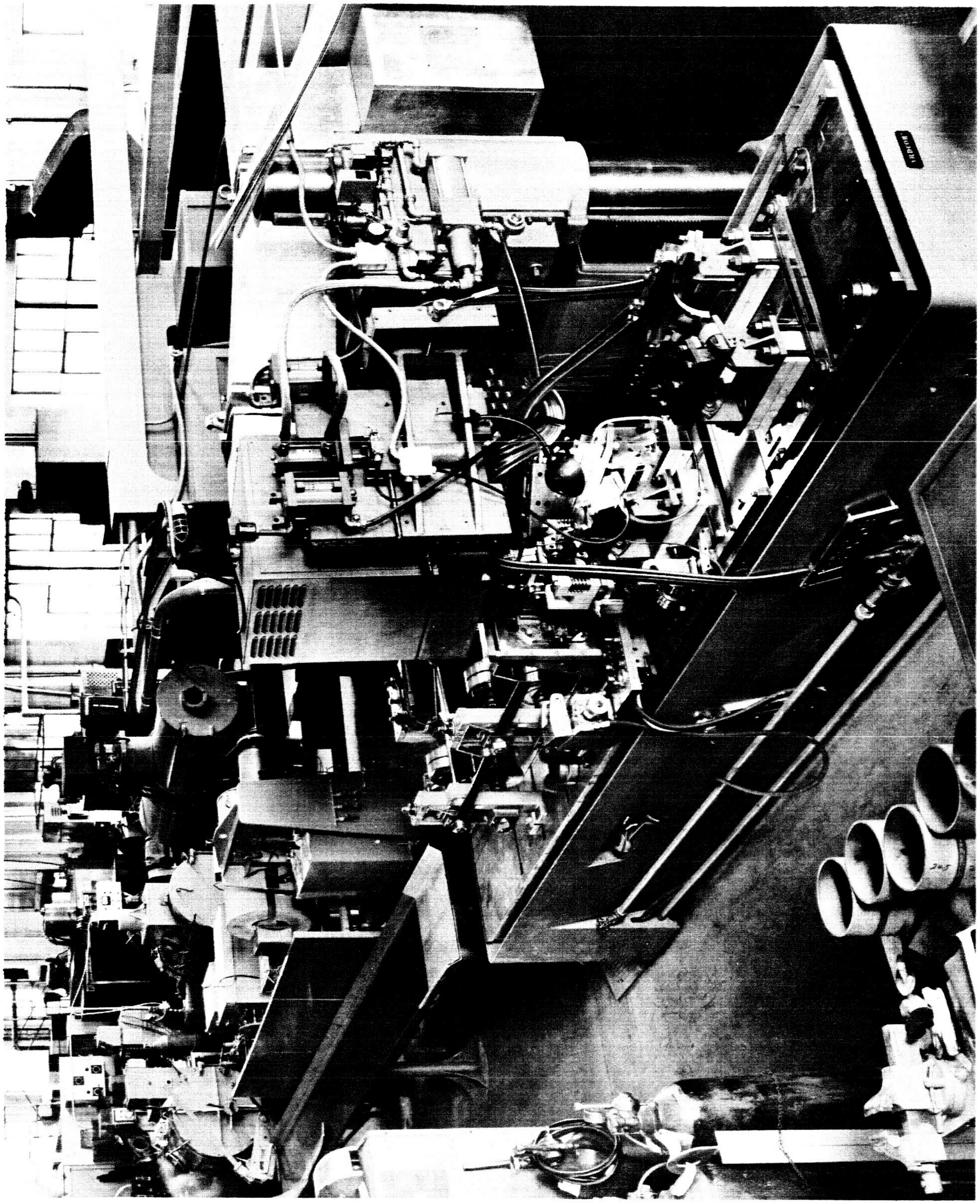


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FIGURE 3. BATTELLE HIGH-FREQUENCY RESISTANCE WELDING FACILITY WITH GUIDES IN POSITION FOR BUTT-SEAM-WELDING OF STRIP

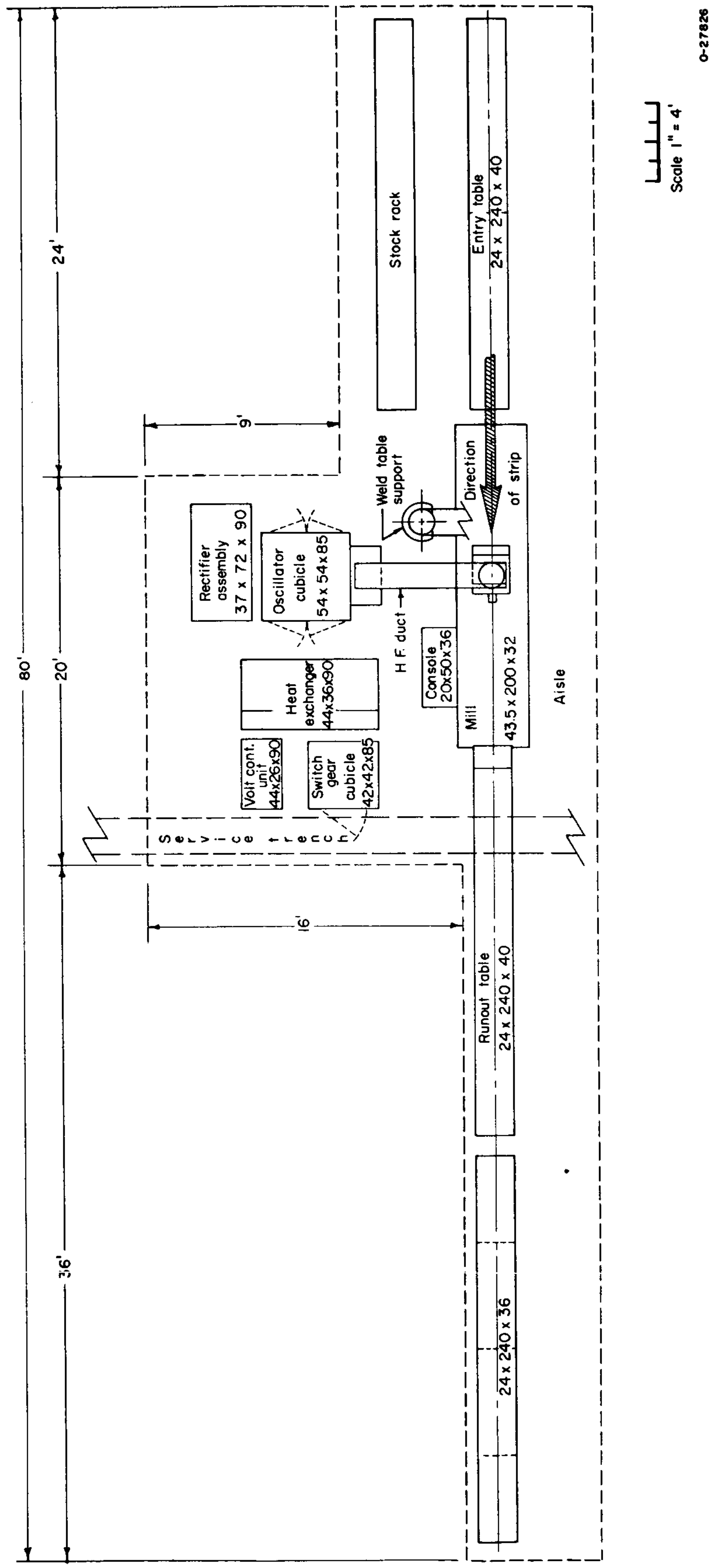


FIGURE 4. FLOOR PLAN OF THE HIGH-FREQUENCY RESISTANCE WELDING FACILITY

and a squeeze-roll unit to force the heated edges of the strips together as they are welded. The fixtures that help to guide and position the strips as they pass through the welding station also are mounted on the mill base. These fixtures have a wide range of adjustment and can be removed, replaced, or modified. A tank and pump for water-soluble oil coolant are located within the mill base. The mill base with the original fixtures in position before installation at Battelle is shown in Figure 5. During the welding studies, it became necessary to modify some of these components to obtain proper welding conditions for making welds in some materials.

The squeeze rolls in the original welding station were mounted in yokes that could be adjusted in the inboard or outboard directions to provide the forging action required to upset the weld. In early studies with low-carbon steel, the amount of upset varied due to flexing of the yoke; also the roll positions required frequent adjustment to change the amount of upset and to permit rethreading the mill. The studies with steel showed that there was a need to provide a system that was capable of providing the greater upsetting forces required for the program materials. In addition, a system capable of providing either a constant upsetting distance or a constant upset force was needed.

To meet this need, the hydraulically actuated squeeze-roll system shown in Figure 6 was designed, fabricated, and installed at the welding station as shown in Figure 7. The information listed below served as a guide in designing the system:

(1) Strip thickness was expected to range from 0.029 to 0.500 inch.

(2) Materials to be welded included AISI 301 stainless steel, on the low end of the thickness range, and aluminum alloys on the high end of the thickness range.

(3) The strips would pass through the welding station ranging from the flat position to a twist of about 45 degrees.

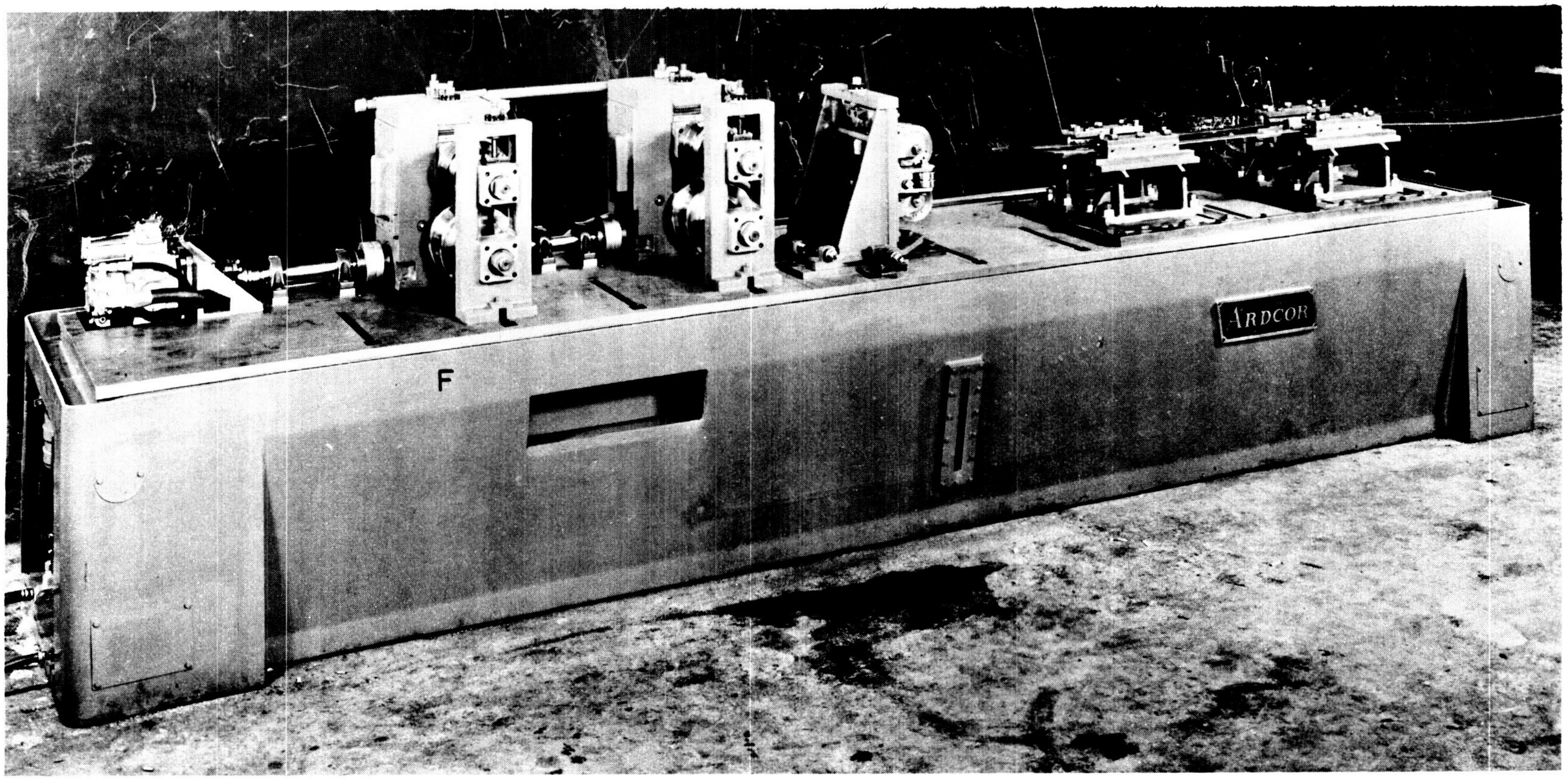
(4) The unit was not to interfere with components or adjustments already installed.

(5) The system should be capable of being moved upstream or downstream.

The squeeze-roll system was designed so that welding could be performed with either a constant upsetting force or with a constant upset distance. For welding with constant upset distance, the squeeze rolls were advanced to a mechanical stop. For welding with constant upsetting force, the stops were removed so the rolls advanced only against the resistance of the material. Each roll was capable of being advanced, retracted or stopped independently.

In early work squeeze rolls which were flat except for a step support for the bottom of the strip were used to apply upset force. With these step squeeze rolls, the outboard edges of the strips were deformed, and the upset force was not uniformly applied to the weld point.

To improve control of the upset, squeeze rolls with a 1/4-inch-deep groove were designed and fabricated. The groove width was made 15 per cent greater than the stock thickness to prevent jamming or bonding in the bottom of the groove. Welds having a



N99351

A - Slide Guide No. 1
B - Slide Guide No. 2
C - Aligning and squeeze rolls and support
D - Pullout Roll Stand No. 1
E - Pullout Roll Stand No. 2
F - Roll-Forming Mill Base

FIGURE 5. WELDING-MILL BASE WITH ORIGINAL PULLOUT ROLL STANDS, WELDING STATION ROLLS, AND SLIDE GUIDES MOUNTED IN POSITION BEFORE INSTALLATION AT BATTELLE

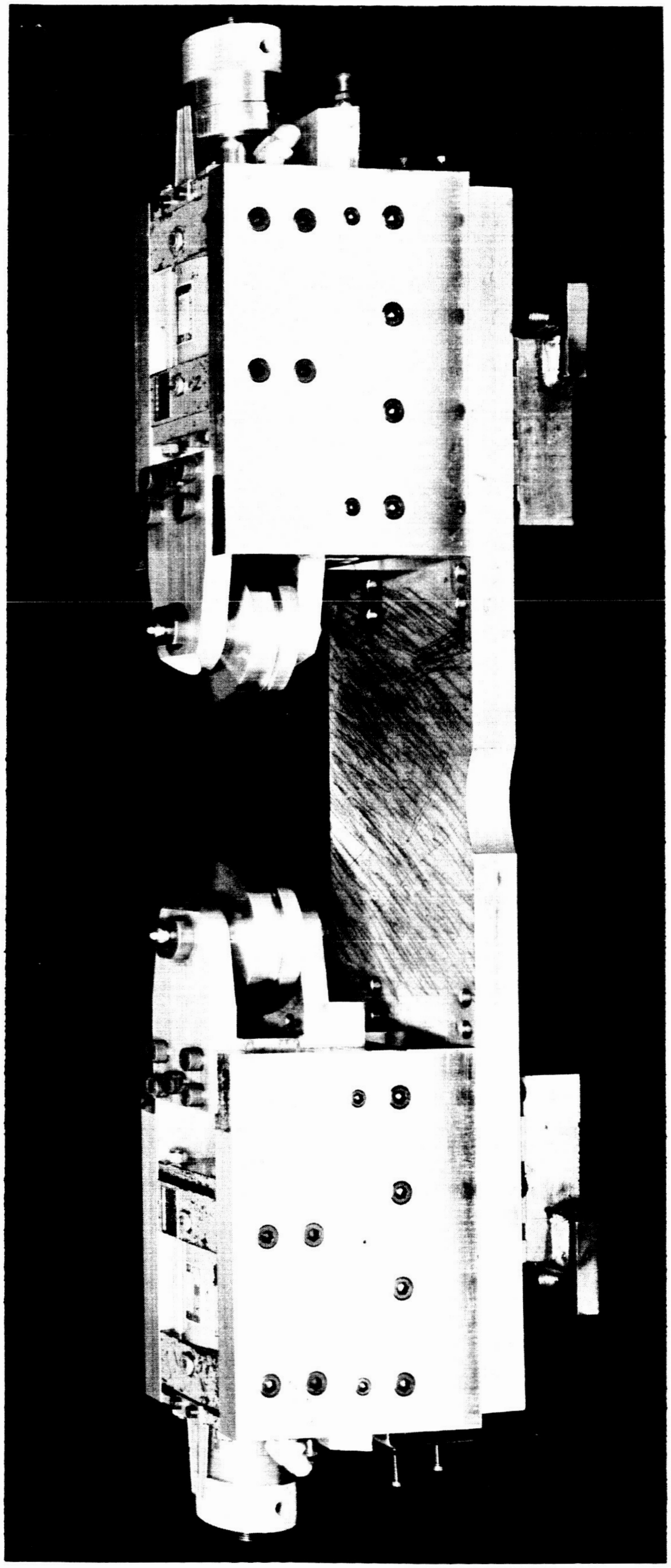


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FIGURE 6. HYDRAULICALLY ACTUATED SQUEEZE-ROLL UNIT

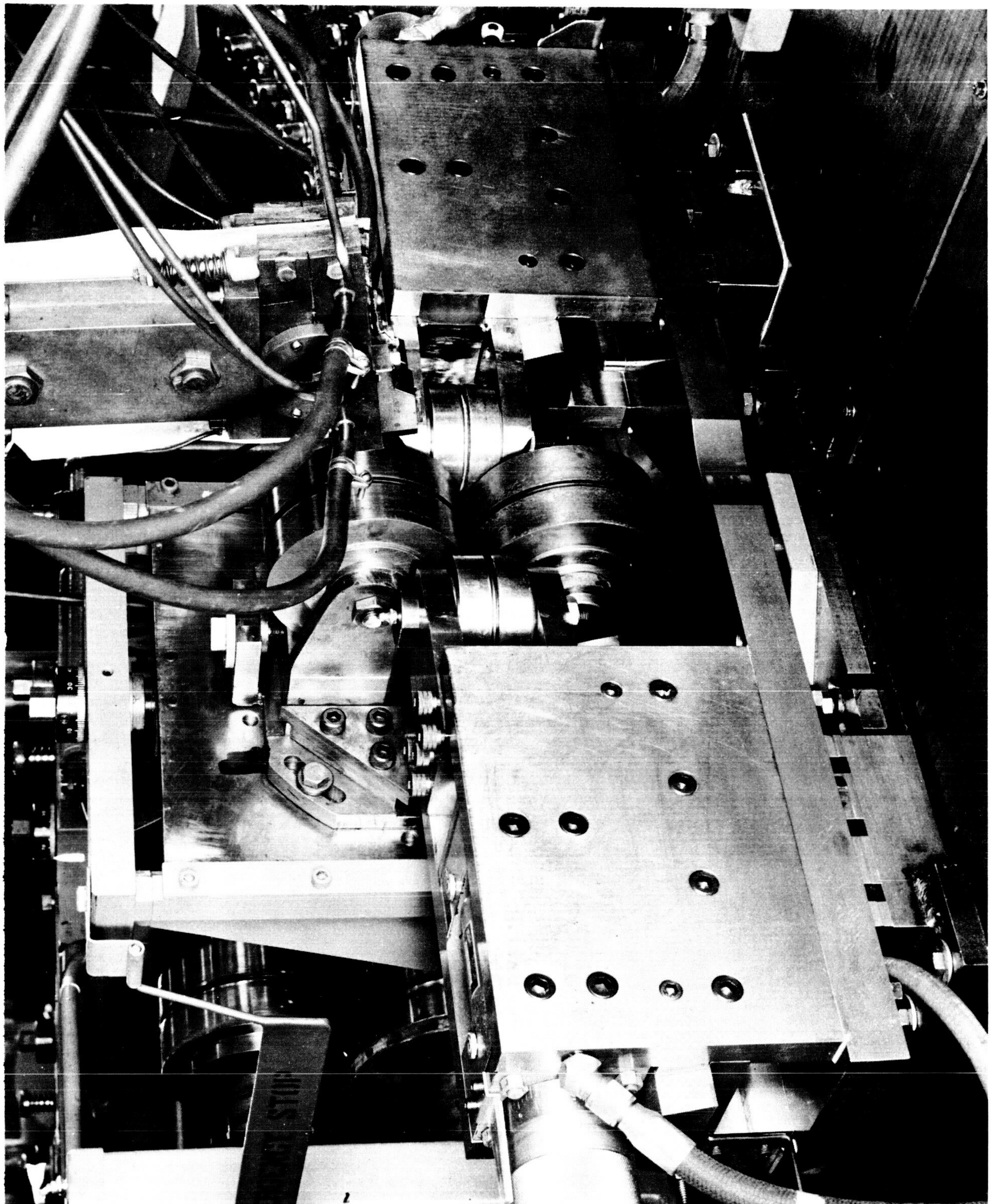

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FIGURE 7. HYDRAULICALLY ACTUATED SQUEEZE-ROLL UNIT INSTALLED AT THE WELDING STATION

consistently good appearance were produced when these grooved squeeze rolls were used to supply the upset.

Welding studies conducted with low-carbon steel strip showed that several guiding methods were amenable to welding this material. The results of these studies showed that special guide tooling probably would be required for some if not all of the program materials. Subsequent experiments with aluminum alloys and stainless steels led to the development of another guide component that was needed to support the strips and guide them into the welding station to form proper vee configurations for the program materials.

The guide was designed, fabricated, and installed immediately upstream from the squeeze-roll unit. This tooling will be referred to as the "primary guide" throughout the balance of this report. The unit is shown in Figure 8. Figure 9 shows the unit after it was installed in position for use in the welding experiments. The primary guide was used to (1) support the strips, (2) twist the strips as they entered the welding station, (3) guide the strips, and (4) form the vee. This guide also provided a simpler method for threading the strips through the equipment and required less plastic deformation of the strips than other methods of forming the vee. The primary guide included several rolls to reduce frictional drag and wear of the strips. The entire primary guide rests on a 7-inch screw to raise or lower its height. The vee formed with the primary guide was established by twisting the strips and raising the elevation of the primary guide above the squeeze point.

MATERIALS

The materials studied in this program included several aluminum alloys, 2014-T6, 7179-T6, and 5456-H343; two stainless steels, AISI 301 and AISI 310 in the full-hard condition, and the titanium alloy, Ti-6Al-4V. The chemical composition limits of these alloys are given in Table 1. The Ti-6Al-4V alloy was available from the Titanium Sheet Rolling Program and was substituted for the Ti-5Al-2-1/2-Sn alloy that was suggested in the proposal. Only annealed titanium alloy was available. Low-carbon steel also was welded during the program to place the welding mill in operation and to develop welding and evaluation procedures for use during the research. AA1100-H14 aluminum alloy also was welded to help establish welding requirements for the aluminum alloys.

The thickness requirements for these materials were based on their capabilities for developing 4,000 to 16,000-lb transverse tensile loads per inch of joint with less than 0.2 per cent permanent set in a 4t* gage length. Since the properties of the joints producible in the program materials with high-frequency welding were unknown, the thicknesses were established on the basis of parent-metal properties. Three thicknesses were selected for each of the stainless steels and two thicknesses were selected for each of the aluminum alloys. The low-carbon steel was 0.109-in. thick. The AA1100-H14 aluminum alloy was 0.093 in. thick, and it was purchased in coils to eliminate constant threading of the mill and to allow preparation of longer welds. The thickness in the titanium-base alloy was selected on the basis of availability of

*t = thickness.

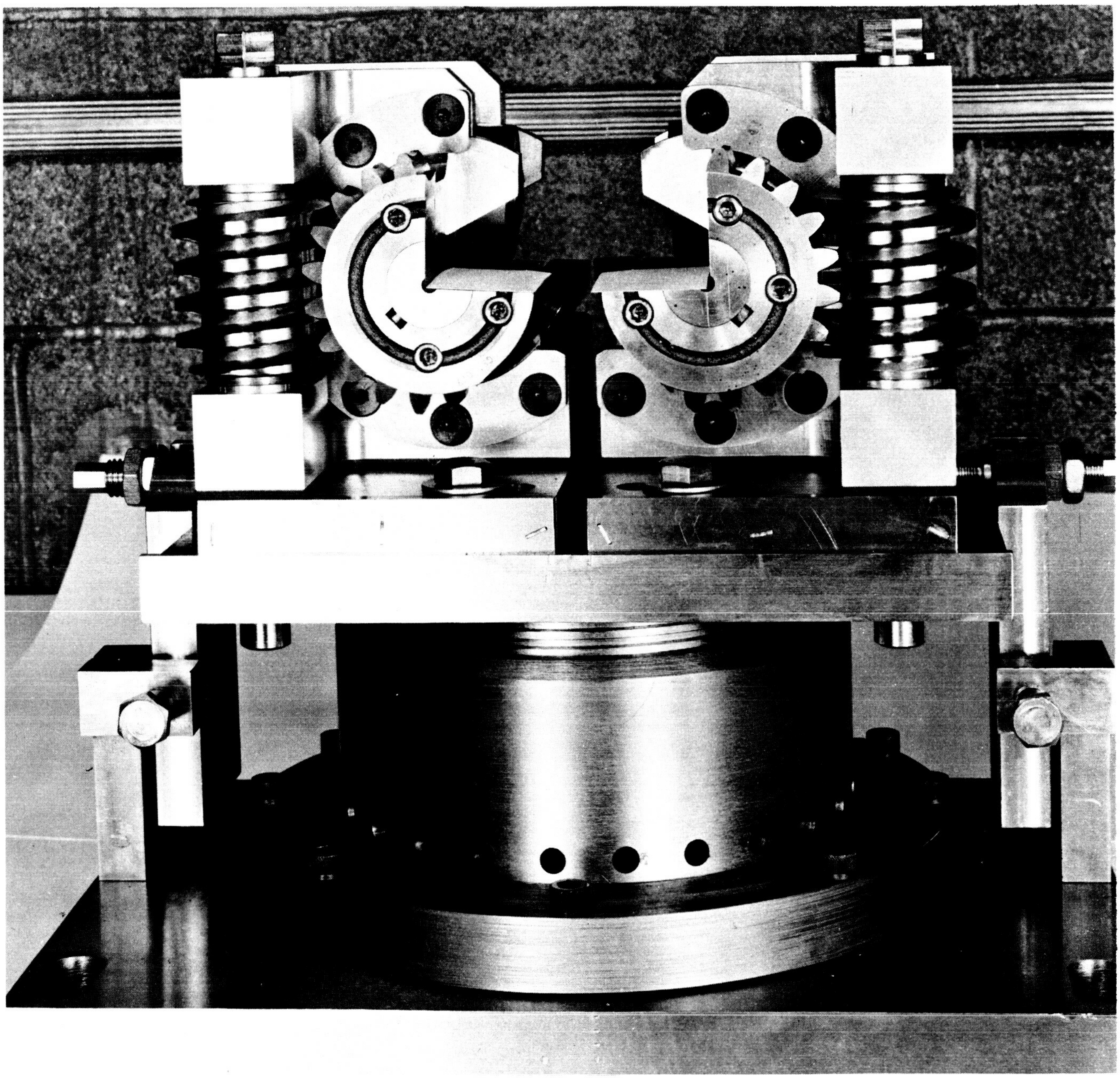

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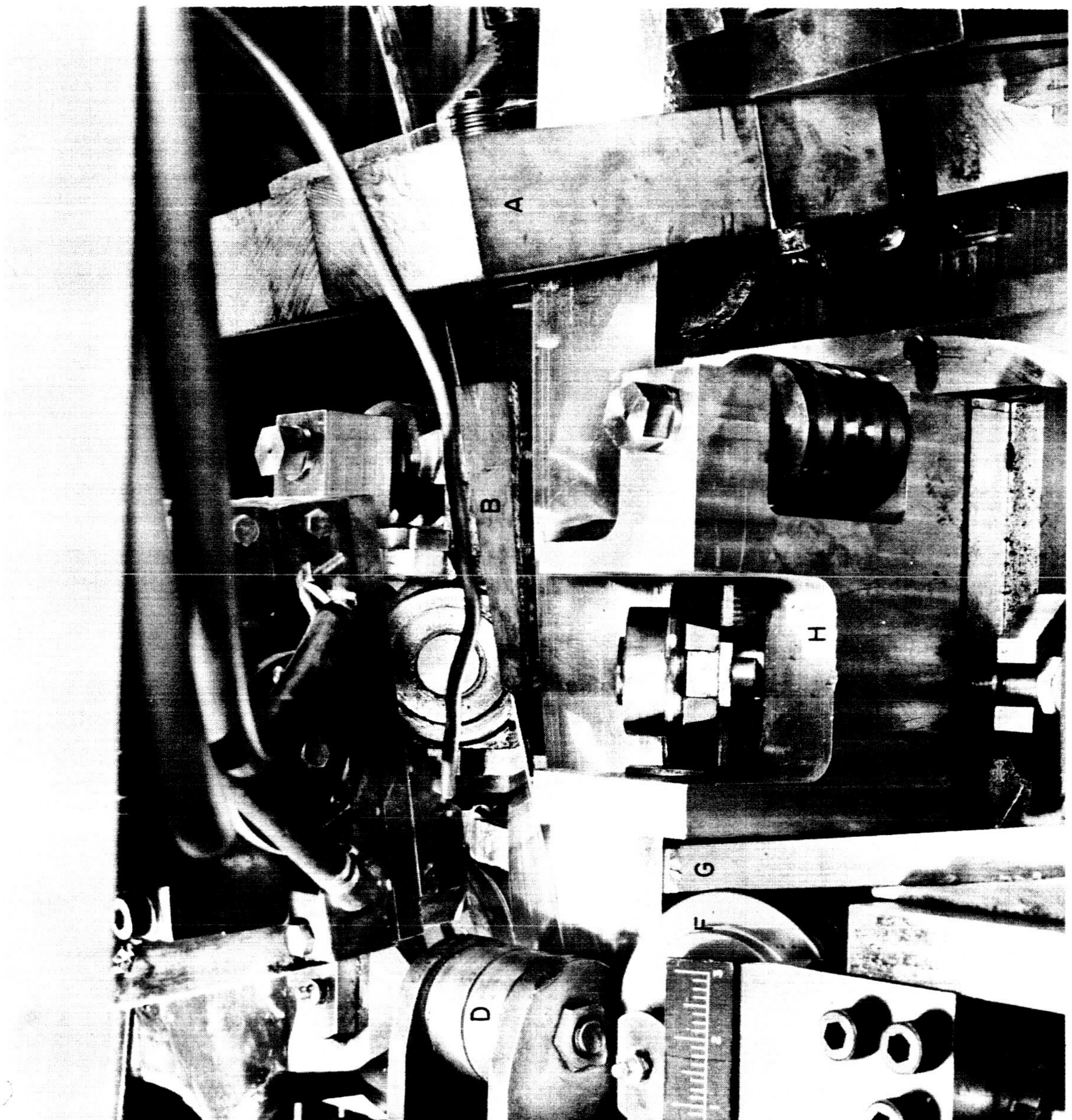
FIGURE 8. PRIMARY GUIDE UNIT BEFORE INSTALLATION FOR WELDING



N99347

A - Strip holder
B - Seam Guide
C - Contact Support
D - Aligning Roll
E - Postweld Guide
F - Squeeze Rolls
G - Strip Edge Support
H - Primary Guide

FIGURE 9. PRIMARY GUIDE UNIT AFTER INSTALLATION AT THE BATTELLE HIGH-FREQUENCY RESISTANCE WELDING FACILITY

TABLE 1. CHEMICAL COMPOSITION LIMITS OF ALLOYS STUDIED IN THE HIGH-FREQUENCY RESISTANCE WELDING PROGRAM

		Aluminum Alloys[a]			
AA2014-T6		AA7179-T6		AA5456-H343	
Si	0.5-1.2	Si	0.15 max	Si + Fe	0.40
Fe	1.0 max	Fe	0.20 max	Cu	0.10
Cu	3.9-5.0	Cu	0.40-0.080	Mn	0.50-1.0
Mn	0.40-1.2	Mn	0.10-0.30	Mg	4.7-5.5
Mg	0.20-0.80	Mg	2.9-3.7	Cr	0.05-0.20
Cr	0.10 max	Cr	0.10-0.25	Zn	0.25 max
Zn	0.25 max	Zn	3.8-4.8	Ti	0.20 max
Ti	0.15 max	Ti	0.10 max	Other	0.15 total
Other	0.15 total	Other	0.15 total	Al	Balance
Al	Balance	Al	Balance		
	Stainless Steel[b]			Titanium[c]	
AISI 301		AISI 310		Ti-6Al-4V	
C	0.15 max	C	0.25 max	Al	5.5-6.75
Mn	2.00 max	Mn	2.00 max	V	3.5-4.5
P	0.045 max	P	0.045 max	N	0.07 max
S	0.030 max	S	0.030 max	C	0.10 max
Si	1.00 max	Si	1.50 max	H	0.015 max
Cr	16.00-18.00	Cr	24.00-26.00	Fe	0.40 max
Ni	6.00-8.00	Ni	19.00-22.00	O	0.30 max
Fe	Balance	Fe	Balance	Ti	Balance

(a) Aluminum Company of America, Certified Inspection Reports.
(b) Steel Products Manual, Stainless and Heat-Resisting Steels, American Iron and Steel Institute, New York (June, 1957), p 8.
(c) Metals Handbook, T. Lyman, Eighth Edition, American Society for Metals, Novelty, Ohio (1961), p 1154.

TABLE 2. MATERIALS USED IN WELDING STUDIES

Material	Nominal Thickness (t), in.	Ultimate Tensile Strength[a], psi	Yield Strength[a] (0.2% Offset), psi	Elongation[a], per cent in 2 in.	Hardness
		Low-Carbon Steel			
AISI C1010, hot rolled, cold finished	0.109	46,900	36,400	33	--
		Stainless Steel			
AISI 301, full hard	0.029	Not welded			
	0.0715	209,700	187,700	5.2	44 R_c
	0.114	191,900	168,000	9	40 R_c
AISI 310, full hard	0.029	Not welded			
	0.0715	148,100	134,400	7.8	33 R_c
	0.114	137,400	126,500	11	27 R_c
		Aluminum Alloys			
AA1100-H14	0.093	--	--	--	--
AA2014-T6	0.068	67,100	60,000	25.3	74 R_b
	0.188	70,400	63,900	13.0	80 R_b
AA5456-H343 (max comm. hardness)	0.093	58,000	45,000	8.3	95 R_b
	0.188	59,200	42,300	13.0	63 R_b
AA7179-T6	0.062	80,000	71,000	12.2	76 R_b
	0.188	82,700	71,300	12.7	89 R_b
		Titanium Alloys			
Ti-6Al-4V, solution annealed	0.032	Not welded			
	0.063	132,500	129,000	12.7	89 R_b
	0.125	Not welded			

(a) Average of 3 tests.

sheets long enough to obtain in strips for the welding studies. Table 2 summarizes the properties and thicknesses of materials acquired for use in the program.

All of the materials that were studied during this program were obtained in the form of strips, 2 inches wide, or sheets that were converted into 2-inch-wide strips by slitting or shearing. The work needed to prepare the strip materials was conducted as part of the program, and is described below.

The aluminum alloys were available only in 10-foot-long sheets. The thinnest aluminum alloy sheets were converted into 2-inch-wide strips by slitting. The 3/16-inch-thick aluminum alloy sheets could not be slit with the same equipment, and it was not possible to find a fabricator with adequate slitting equipment. Therefore, it was necessary to find another way of converting the thick aluminum sheets into strip. After evaluations showed that the strip width tolerances could be maintained, the sheet was converted into strips by shearing. The edges produced on the strips by shearing were comparable with the edges produced by slitting the thinner aluminum alloys.

The stainless steel strips were available in 20-foot-long strips with square-rolled edges. The low-carbon steel was available in strips 12 ft long and the titanium-6 aluminum-4 vanadium alloy was available in 10-foot-long sheets which were converted into strips by slitting. Except for stainless steel, the materials were welded with the edges in the as-slit or as-sheared condition. After the low-carbon steel was slit, the edges were oiled to prevent rusting, but before welding, the edges were wiped clean with organic solvents.

It was originally planned to prepare strips that were 20 to 30 ft long and thread them through the mill for each welding experiment. However, only the stainless steel was available in 20-ft-long strips. Therefore, strips of other materials were butt welded end to end to form longer strips. The steel strips were flash welded and the aluminum alloy strips were welded by the tungsten inert-gas-shielded welding process. Early in the program it was learned that rethreading the mill for each weld experiment was costly and time-consuming. Therefore, the butt-welding practice used for joining strip ends was adapted to attaching the leading edges of one pair of strips to the trailing edges of strips already in the mill. By doing this, each new pair of strips was automatically threaded through the mill.

EXPERIMENTAL PROCEDURES

Standardized experimental procedures were used in much of this research to achieve the research objectives at minimum cost. A complete checkout of the welding facility was made as the final step to insure that each of the components functioned properly. Then initial experimental welds were made to ascertain proper operation of the high-frequency power supply, drive system, and the initial tooling, and to establish experimental procedures for use during the balance of the program.

To prepare for the welding of strips, the squeeze rolls were retracted. Then the strips were threaded through the slide guides, primary guide, welding station, aligning rolls, and into the pullout rolls. After the guides were adjusted, the squeeze rolls were closed and adjusted to provide the desired upset force or upset distance.

Then the upstream-downstream position of the aligning rolls was adjusted, usually to a position about 1/32 of an inch downstream from the squeeze rolls. The strips then were inched forward to allow the strips to come to an equilibrium position, and measurements were made of the vee. After the desired vee geometry was achieved, the weld was made.

For making the weld, the hydraulic drive was actuated and the strips were accelerated to welding speed. After the strips reached welding speed, the welding power supply was energized. To expedite the determination of the proper welding power range, preliminary welds were made using an upsloped power output from the generator. The upsloped welding power was used to provide a known increasing range of welding power to study the effects of various power-input values and to help select the proper power range for making subsequent welds with constant welding power.

Weld Evaluation

The characteristics and properties of all welds made were evaluated. The evaluations normally conducted were

(1) Visual observations during welding

(2) Visual examinations of completed welds

(3) Bend tests

(4) Tension tests

(5) Metallographic examinations

(6) Hardness determinations.

During welding, visual observations were made to observe the behavior of the strips, heating patterns and arcing in the vee. Changes in the shape of the vee, changes in the location of the vee apex, and improper passage of the strips through the mill were detected quickly so the mill and power supply could be de-energized.

The following visual examinations of the completed welds were made to observe the surface characteristics of the welds:

(1) Appearance of flash

(2) Appearance of upset

(3) Surface oxidation patterns for uniformity of heat input

(4) Comparison of top and bottom of the welds

(5) Alignment of the strip edges

(6) Contact markings (burns or scratches)

(7) Uniformity of electrical contact

(8) Arc burns.

Results of the observations and the locations of unusual weld characteristics were noted for comparison with results of later evaluations, and metallographic and mechanical-properties data.

Transverse bend tests were used as a weld-evaluation method that could be conducted soon after the weld was completed. The bend tests were conducted using samples, containing from 1/2 to 4 inches of weld, that were sheared from the completed 4-in.-wide weldment. The bend tests were used to quickly establish weld soundness from the fracture surface appearance, and to estimate the strength of the welds. These observations combined with the results of the visual examinations of the weld provided information on weld quality that was used in evaluating and adjusting welding conditions.

Strength data for the weldments were obtained using two types of specimens. One specimen, shown in Figure 10a, was used for evaluating weld strength as soon as possible after welding. Information was needed often on weldment strength before changing to new welding conditions. To obtain the needed data, transverse weld sections, 1/2 to 3/4 inch wide, were sheared from the completed weldment and were pulled in tension. Welding conditions were modified on the basis of data obtained from these somewhat rough tension tests. The second type of tension specimen was the machined specimen shown in Figure 10b. This specimen was prepared from a coupon sheared from the weldment. The reduced cross section was machined, and the flat surfaces were finished by grinding. The machined specimen was used for determinations of ultimate tensile strength and, when possible, yield strength and elongation.

Many of the welds were examined by standard metallographic procedures. The metallographic examinations were made to establish weld characteristics such as heat-affected-zone width, the presence or absence of cast metal and defects, and to study the consistency of weld quality along the welded seam. Hardness determinations also were made on a number of the cross sections.

Studies With Low-Carbon Steel

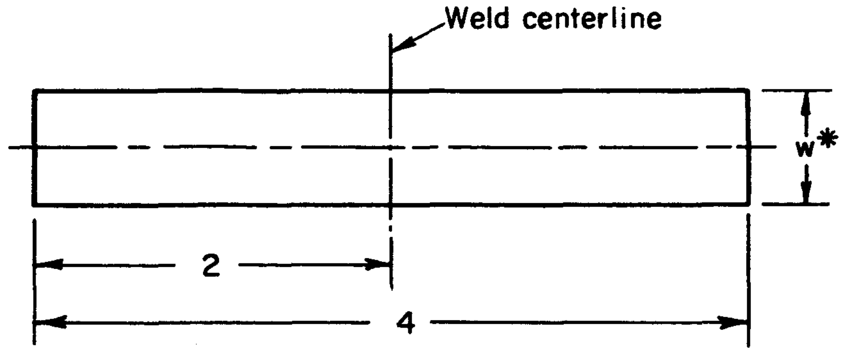
Low-carbon steel strips were used for the initial evaluation of the high-frequency power supply, the initial strip guide system, and instrumentation. Welds were made using several methods to guide the strips past the welding station and to establish the vee shapes that would be used for welding strips of the program materials. The guiding methods used to form the vee with mild steel strips included

(1) Flat-position guiding method

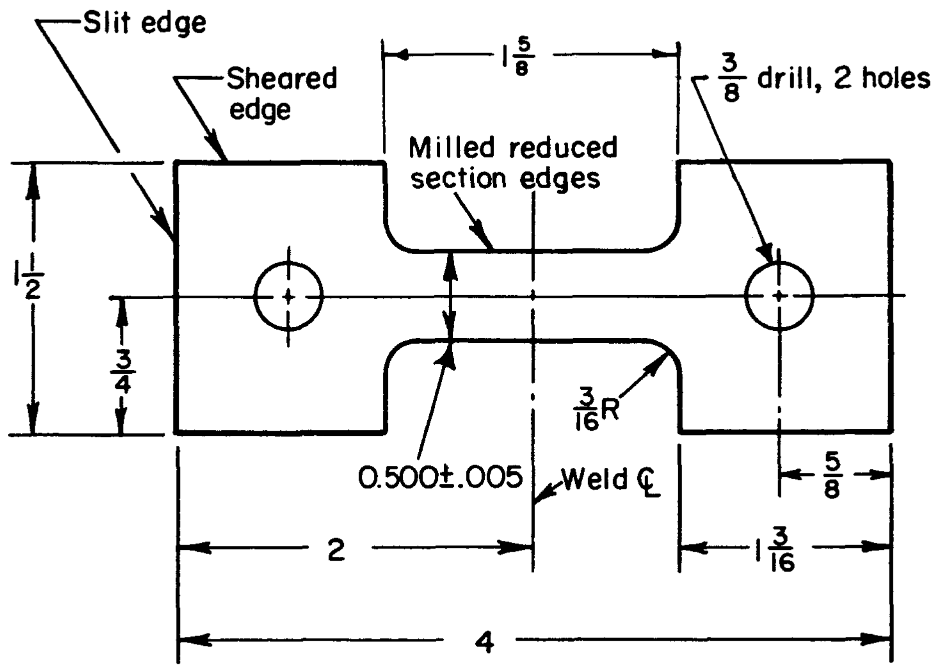
(2) Dual-elevation guiding method

(3) Twisting, elevating, and forcibly separating guiding method.

Welding conditions were established early in the program for welding mild steel with each of these guiding methods.



(a) Sheared tension specimen
* w = 0.5 to 0.75 in.



(Grind thickness to clean up) Scale 1" = 1"

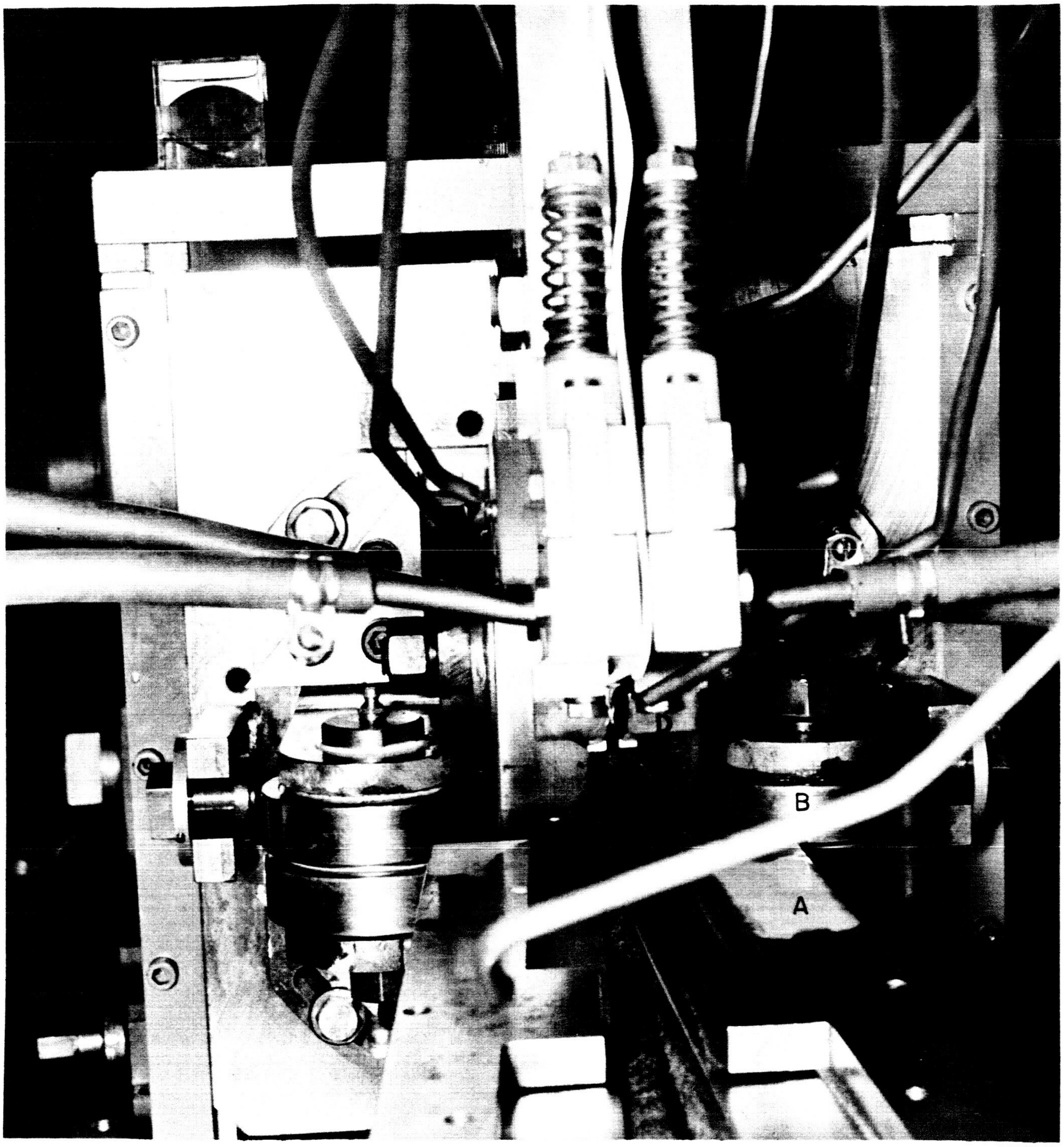
(b) Machined tension specimen A-44748

FIGURE 10. TENSION TEST SPECIMENS FOR EVALUATING HIGH-FREQUENCY RESISTANCE WELDED SPECIMENS IN 4-IN.-WIDE WELDMENTS

Initial welding tests were carried out with the strips guided through the welding station in the flat position. The tooling required to do this was relatively simple and inexpensive. These studies were made to establish initial welding conditions and characteristics of the vee for making satisfactory welds. The fixtures and guides used for making initial welds in the flat position with steel strips are shown in Figure 11. While welding with low-carbon steel, evidence of irregular heating was observed. The irregularities in heating were caused by sudden slippage of the strips in the pullout rolls and by variations in the position of the squeeze rolls. To eliminate slippage, the strip guides were readjusted to reduce drag from friction and the drive rolls were tightened. In addition, the hydraulically actuated squeeze-roll unit was installed to provide more positive and controllable upset. These modifications eliminated the heating irregularities. The studies showed that the strips buckled on the downstream side of the squeeze point. Typical variations in the buckling that occurred are shown in Figure 12. The buckling was considered to be a potential source of weld cracking and a slide guide was installed immediately downstream from the squeeze point to provide good containment of the strips and eliminate the buckling. Welding conditions developed for welding the steel strips and results of strength test are reported in Table 3. Low-carbon steel was easy to weld in the flat position and, as indicated by the results, 100 per cent joint efficiencies could be obtained.

Another method for forming the vee in which each strip entered the welding station from a different elevation was evaluated. With this method the vee was formed in the vertical plane. With this guiding method the top edge of the lower strip and the bottom edge of the top strip were overheated because of the proximity effect. Furthermore, the heated edges of the strips were not butted together squarely but were brought together with a wiping or shearing action. However, good welds could be made with this guiding method as shown by the transverse cross section in Figure 13. The breaking strengths and joint efficiencies of several welds made with this guiding method were given in Table 3. This method of strip entry approximates the vee formed and the welding conditions during spiral welding and it appears easy to weld mild steel with this guiding method.

The requirements and design of a guide to contain and twist the strips as they approach the squeeze point were determined and evaluated initially with mild steel. The apparatus and guide system developed worked satisfactorily for mild steel without further development work. The welds obtained showed good weld upset and the general appearance of these welds was the same as earlier good welds in mild steel. This method of strip entry was later used for obtaining the vee for welding the program materials.



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A - Strip Guides
B - Squeeze Roll
C - Aligning Roll
D - Electrical-Contact Shoes

FIGURE 11. VEE FORMED IN THE FLAT POSITION WITH LOW-CARBON STEEL STRIP

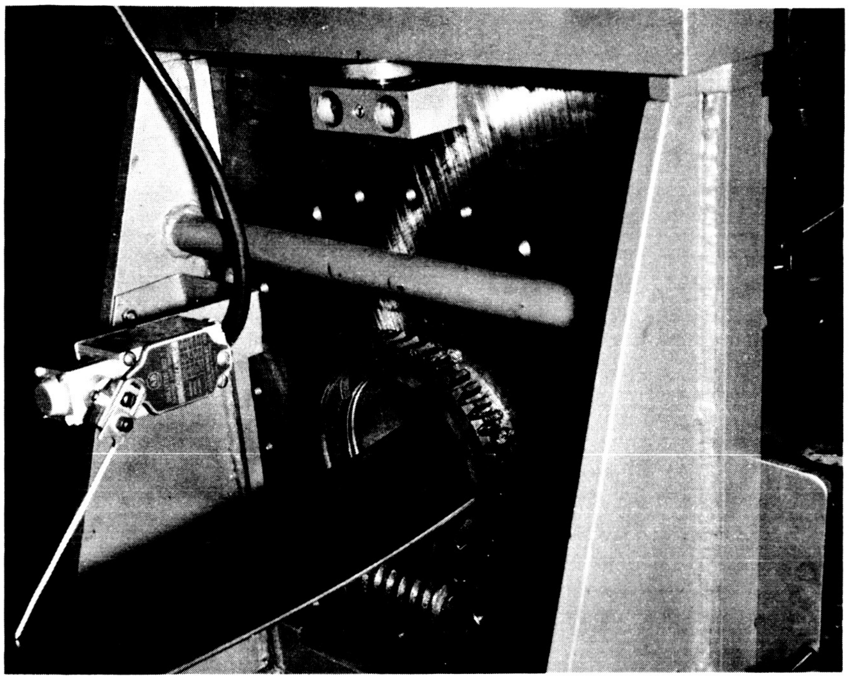

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FIGURE 12. BUCKLING IN UNWELDED STRIPS OF LOW-CARBON STEEL BEFORE A POSTWELD GUIDE WAS ATTACHED TO THE MILL

TABLE 3. SUMMARY OF WELDING CONDITIONS AND RESULTS FOR SATISFACTORY WELDS IN 0.109-INCH-THICK LOW-CARBON STEEL

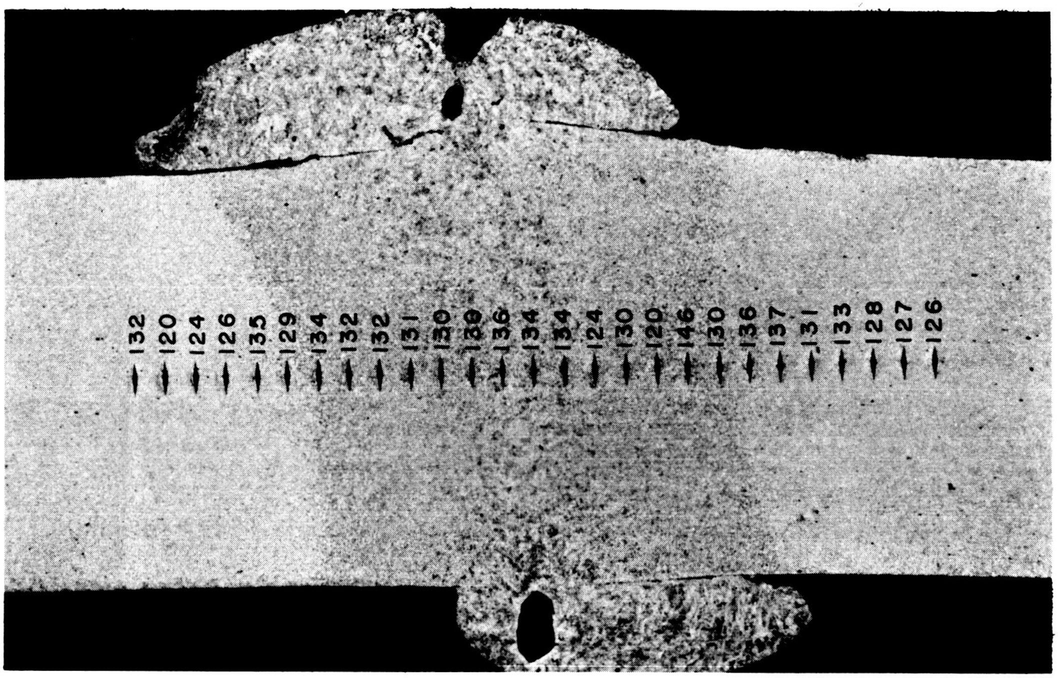
Weld No.	Power Setting,[a] volts	Preset Upset Distance, mils	Welding Speed, fpm	Strip Separation at the Contacts, inch	Arcing at Vee, Yes/No	Ultimate Tensile Strength,[b] Range, ksi	Joint Efficiency, per cent	Location of Failures[c]	Remarks
				Flat-Position Guiding Method[d]					
FJ20	478(D)	71	250	0.231	No	56.3/58.1 (4)	100	UBM	--
FJ21	478(D)	88	250	0.231	No	55.6/57.1 (3)	100	"	--
FJ23	485(D)	85	250	0.231	No	55.1/57.5 (4)	100	"	--
				Dual-Elevation Guiding Method[e]					
FJ4	360(D)	30	100	0.11 x 0.25	No	53.6/54.8 (2)	100	UBM	--
FJ6	370(D)	30	100	0.11 x 0.25	No	41.0/57.5 (2)	71-100	W + UBM	--
FJ7	370(D)	45	100	0.11 x 0.25	No	56.7/58.2 (2)	100	UBM	--
FJ8	360(D)	95	100	0.11 x 0.25	No	55.0/58.0 (5)	100	"	--
FJ9	370(D)	45	100	0.11 x 0.25	No	53.7/58.6 (4)	100	"	--
FJ10	530(D)	45	240	0.08 x 0.25	No	35.6/58.2 (4)	60-100	W + UBM	Overheated at start of weld
FJ11	540(D)	45	365	0.08 x 0.25	No	11.8/44.4 (3)	21-78	W	Cold weld

(a) (D) indicates a delta-to-wye transformer coupling (high power range).
(b) The number of specimens tested is given in parentheses.
(c) W = weld; UBM = unaffected base metal.
(d) Conditions held constant:

Angle of twist at guides - - - - - - - - - - - - 0 deg.
Angle of twist at contacts - - - - - - - - - - - 0 deg.
East strip elevation - - - - - - - - - - - - - - 0 in. per in.
West strip elevation - - - - - - - - - - - - - - 0 in. per in.
Contact to squeeze-roll centerline distance - - 3.9 in.
Contact to strip edge distance - - - - - - - - - - - 0 in.
Contact-shoe material - - - - - Mallory Elkonite 10W3
Contact-shoe width - - - - - - - - - - - - - - 1/4 in.
Contact-shoe cooling - - - - - - - - water-soluble oil

(e) Conditions held constant:

Angle of twist at guides - - - - - - - - - - - - 13 deg
Angle of twist at contacts - - - - - - - - - - - 22 deg
East strip elevation - - - - - - - - - - - - - - 0 in. per in.
West strip elevation - - - - - - - - - - - - - - 0.064 in. per in.
Contact to squeeze-roll centerline distance - - 3.8 in.
Contact to strip edge distance - - - - - - - 0.22 inch
Contact-shoe material - - - - - Mallory Elkonite 10W3
Contact-shoe width - - - - - - - - - - - - - - 1/4 in.
Contact-shoe cooling - - - - - - - - - water-soluble oil



20X 2% Nital Etch 649

Weld Number FJ 7

Power setting-370 volts (delta)	
Welding speed	100 fpm
Vertical vee width	0.25 inch
Horizontal vee width	0.11 inch
Preset upset distance	0.049 inch

FIGURE 13. TRANSVERSE CROSS SECTION OF A HIGH-FREQUENCY RESISTANCE WELD IN LOW-CARBON STEEL MADE USING THE DUAL ELEVATION GUIDING SYSTEM

Upset would be removed before service. The Knoop Hardness traverse made using a 500-gram load shows only small changes in hardness in the weld area.

PHASE I

Determine the weldability and resultant mechanical properties of the following alloys and conditions: 2014-T6 aluminum, 5456 aluminum in maximum commercial hardness, 7179-T6 or 7075 aluminum alloy, 301 full-hard stainless steel, 310 full-hard stainless steel, and A-110AT titanium alloy in maximum commercial hardness.

PHASE I

WELDABILITY AND PROPERTIES OF HIGH-FREQUENCY RESISTANCE WELDS IN SPACE-LAUNCH-VEHICLE MATERIALS

The objectives of Phase I were to determine the weldability and resultant mechanical properties of high-frequency resistance welds in selected alloys. Welding conditions for making good welds in mild steel were developed early in the program after only minor modifications were made to the original strip guide tooling. These studies demonstrated the capabilities of the process and versatility of the tooling arrangements for welding steel. After satisfactory operation of the mill was achieved, the program was continued to study the adaptability of the process for welding the aluminum, stainless steel, and titanium alloys in which NASA was interested. The conditions required for welding these alloys were, in general, different from the conditions required for welding mild steel. Because of the differences, detailed studies were required to establish proper guiding arrangements in addition to establishing weldability of the program materials and resultant mechanical properties. To establish weldability, welding conditions were developed by studying the influence of welding variables on weld quality.

Results of the Phase I studies showed that each material evaluated in the welding experiments was weldable with the high-frequency resistance welding process when a suitable vee configuration was obtained and controlled during welding. High joint efficiencies were obtained with each type of alloy. The stainless steels appear to be the most weldable. With stainless steels, welding results were more consistent and wider ranges of welding conditions could be used to produce acceptable-quality welds. The ranges of welding conditions required to produce satisfactory welds in aluminum alloys were narrow. With titanium-6 aluminum-4 vanadium alloy, which was substituted for the A-110AT alloy, weldments having high-joint efficiency also were made.

The following sections cover the procedures, results, and a discussion of the welding of the alloys studied in this program.

ALUMINUM ALLOYS

Welding studies were started with aluminum alloys to determine if these alloys could be welded using procedures that were satisfactory for welding low-carbon steels. When it was found that aluminum alloys were not weldable with these procedures, new welding conditions were developed. The aluminum alloys used in the study were 2014-T6, 5456-H343, 7179-T6, and 1100-H14. The 1100 and 5456 aluminum alloys were used for exploratory welding experiments to obtain the needed preliminary information to develop welding conditions and welding requirements. The 2014-T6 and 7179-T6 alloys were then used in more detailed studies to establish weldability and the mechanical properties of high-frequency resistance-welded joints. The procedures which were used in welding the aluminum alloys, the results obtained, and a discussion of these results are covered in the following sections.

Procedures

Initially, welds were made in the 1100 and 5456 alloys using the flat guide system that had been employed successfully in the welding of low-carbon steels. This guiding system did not work well with the aluminum alloys. Other guiding systems that involved forcible separation of the strips were tried, but buckling of the strip caused erratic welds. Subsequent welds were made successfully using either twisting alone or a combination of twisting and elevating the strips as a guiding method. Table I-1 summarizes the range of welding conditions used in exploratory welding experiments with the 5456 aluminum alloy. Most of these experiments were run using an upslope power input at the beginning of the weld. Typical conditions evaluated for representative welds made in this manner are given in Table I-2.

Experimental studies were made with the 2014-T6 alloy to investigate the effects of the following welding variables:

(1) Vee width

(2) Power level

(3) Welding speed (also minor speed variations)

(4) Upset distance

(5) Upset force

(6) Contact position

(7) Contact cooling

(8) Contact to squeeze-roll centerline distance.

Welding conditions used in the studies on 2014-T6 aluminum alloys (0.068 inch thick) are summarized in Table A-I, Appendix A and are discussed in the following paragraph.

The effect of changing the vee width was studied by making welds at 90 fpm with either a 125- or a 160-mil strip separation, measured 1.7 inches upstream from the squeeze-roll centerline. The effects of power level, upset distance, and welding speed were studied in interrelated experiments. The welding speeds employed were 90, 160, and 360 fpm. The upset distance was varied from 136 to 238 mils in 34-mil increments. Between 2 and 5 power settings [ranging from 335 to 550 volts (wye)] were studied for each value of upset distance and speed. A study also was made to determine the effects of changing the welding speed by 20 fpm while the other welding variables remained constant. This change was equivalent to a speed variation of 13 per cent. The effect of controlling upset by applying a fixed upset force without stops provided to limit the upset distance was investigated. The welds in this study were made at two power settings with 3000 pounds of upset force, and at one power setting with 2400 and 3750 pounds of upset force. The effect of changing the position of the contact with respect to the strip edge was studied in two ways. First, the contact-to-strip edge distance was changed, and welds were made at three power settings. Contact-to-edge distances of 45 and 100 mils were used with power settings of 390, 400, and 410 volts. Three power settings

TABLE I-1. SUMMARY OF THE RANGE OF CONDITIONS STUDIED FOR WELDING 0.093-INCH-THICK AA 5456-H343 ALUMINUM ALLOY

	Minimum Value		Maximum Value
Welding Speed, fpm	40		180
Contact-to-Squeeze Roll Centerline Distance, inches	1.7		3.5
Squeeze Roll-to-Vee Apex Distance, inch	-0.030		+0.045
Angle of Twist at Primary Guides, degrees	0		36
Elevation of Primary Guide Above Centerline, inch	0		0.88
Strip Separation at the Contacts, inch	0.090		0.373
Contact-to-Edge Distance, inch	0		0.235
Contact Shoe Material	Elkonite 10W3	and	Elkonite G17
Contact Shoe Width, inch	1/4		1/2
Preset upset Distance, inch	0.040		0.220
Constant Upset Force, pounds	1500		2250
Input Volts (Power), volts	420 (Y)[a]		410 (D)[b]
Contact Cooling	No cooling		Water-soluble oil

(a) (Y) indicates a wye-to-wye transformer coupling (low power range).
(b) (D) indicates a delta-to-wye transformer coupling (high power range).

TABLE I-2. TYPICAL WELDING CONDITIONS AND RESULTS FOR WELDS IN 0.093-INCH-THICK AA5456-H343 ALUMINUM ALLOY[a]

Weld No.	Power Setting,[b, c] volts	Preset Upset Distance, mils	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Backup Force at Squeeze Rolls, lb	Arcing Observed at the Vee	Contact to Edge Distance, mils	Location of Fracture	Remarks
FJ-1236	340(Y) to 480(Y)	200	180	360	2250	Yes	100	W[d]	Bend tests show incomplete bonding
FJ-1238	340(Y) to 420(Y)	220	180	350	2250	Yes	105	W	Bend tests show incomplete bonding

(a) Conditions held constant except as noted in the table:

Radial angle at guides	- 25 deg	Contact shoe material	- Mallory Elkonite G17
Radial angle at contacts	- 17 deg	Contact shoe width	- 1/4 inch
Elevation at primary guides	- 3/4 inch	Contact shoe cooling	- Soluble oil coolant

Distance between squeeze-roll centerline and contacts - 3-1/2 inches

(b) (Y) indicates a wye-to-wye transformer coupling (low power range).
(c) An upsloped power input was used in the range shown.
(d) W = Weld.

were used to insure that the change in impedance associated with changing the contact-to-strip edge distance would not affect the results. Another experiment was run to determine the effects of positioning one contact on the strip edge, and the other 250 mils in from the edge. In this experiment the other welding conditions were 238-mil preset upset distance, 410 volts (wye) power setting at 160-fpm welding speed. Welding conditions similar to those mentioned just above were used in an experiment with the contact positioned normally and the effects of not employing a contact coolant were studied. The effects of changing the contact-to-squeeze roll centerline distance was determined by comparing two welds in which this distance was varied by 50 per cent (from 1.7 to 2.55 inches). The other welding conditions were a preset upset distance of 204 mils, a welding speed of 160 fpm, and a power setting of 425 volts (wye). A higher power input had to be used with the greater contact-to-squeeze roll centerline distance, since increasing this distance increases the time available for heat losses to occur.

Experimental studies were made with the 7179-T6 aluminum alloy (0.063 inch thick) to evaluate its weldability. The same aligning and guiding arrangement used for making the welds in the 2014-T6 alloy was employed. Welds were made at those conditions that had previously been found to produce the best weldments in the 2014-T6 alloy. Power settings of 340 and 350 volts (wye) were used to make welds when the strip separation was 120 mils under the contact shoes. Power settings of 330, 340, and 350 volts (wye) were used with a 110-mil strip separation. All welds were made using a preset upset distance of 186 mils and a welding speed of 160 fpm. Welding conditions used in studies of 7179-T6 alloy are summarized in Table A-2, Appendix A.

Results

The results of the exploratory welding experiments made with the 5456 and 1100 aluminum alloys showed that a wider strip separation than had been employed for steel was needed on aluminum to prevent arcing during welding. To provide this strip separation it was necessary to form a vee by twisting the strips as shown in Figure I-1. This guiding system was selected for use in welding the remaining alloys in the program, and with minor modifications proved quite adaptable for use in the remaining welding experiments.

The use of upslope power input to establish the optimum power level was found to be a good technique. The usefulness of this technique is illustrated in Figure I-2. This figure shows cross sections taken at intervals of 5, 15, and 25 inches along the initial length of weld. As shown in this figure, only the section cut at 15 inches exhibited the desirable characteristics of a high-frequency resistance weld.

The results of the experiments conducted with the 2014-T6 aluminum alloy are summarized in Table I-3 and in the following listing:

(1) Arcing occurred in the vee in weldments made at 90 fpm with a strip separation of 125 mils. Arcing did not occur when the welding speed was increased to 160 fpm or higher with the same strip separation. Arcing at the vee was eliminated at 90 fpm when the strip separation was increased to 160 mils.

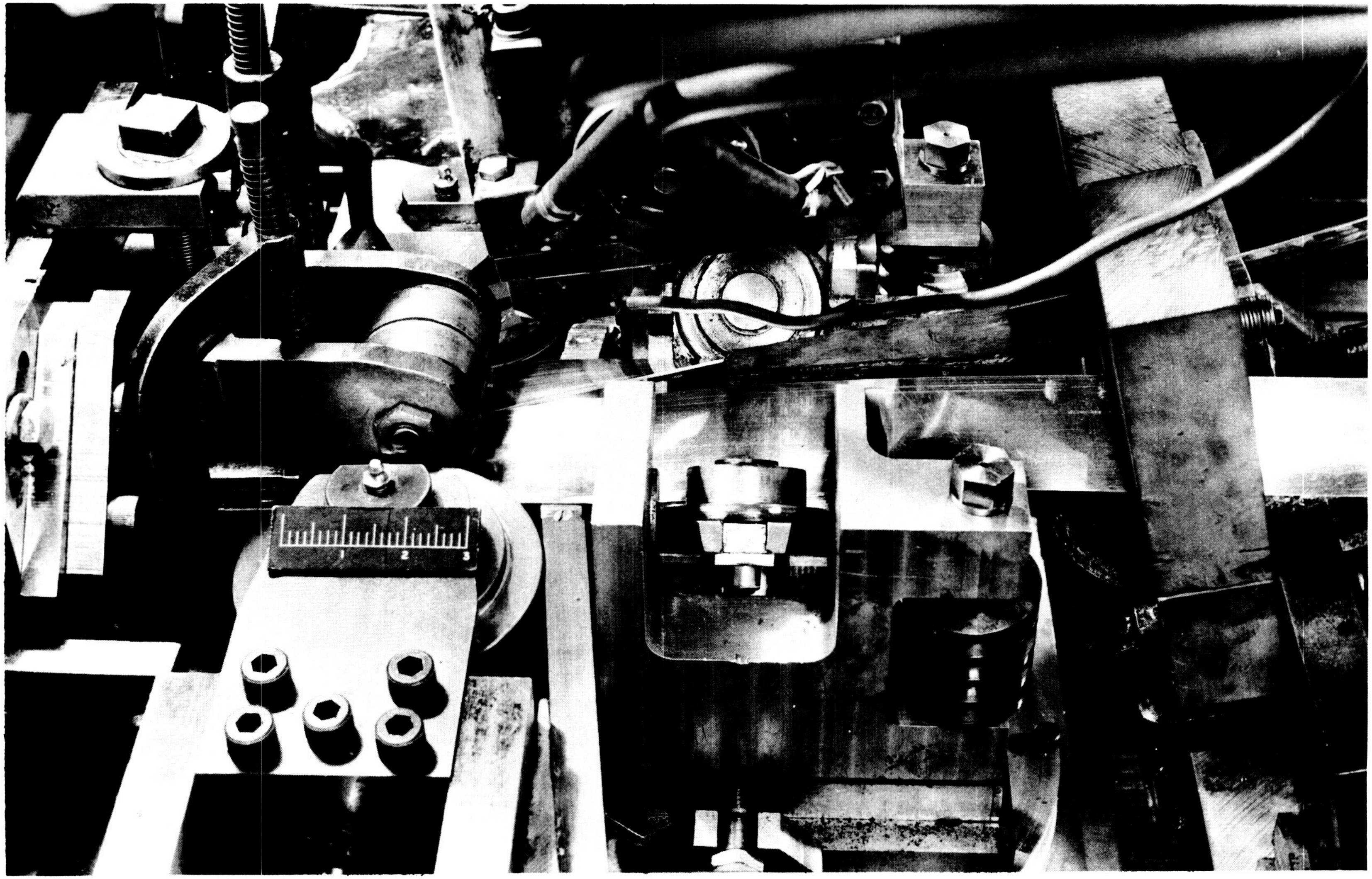


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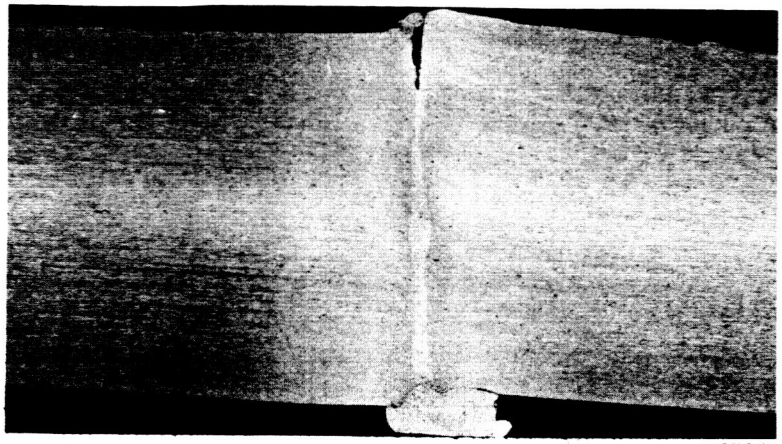
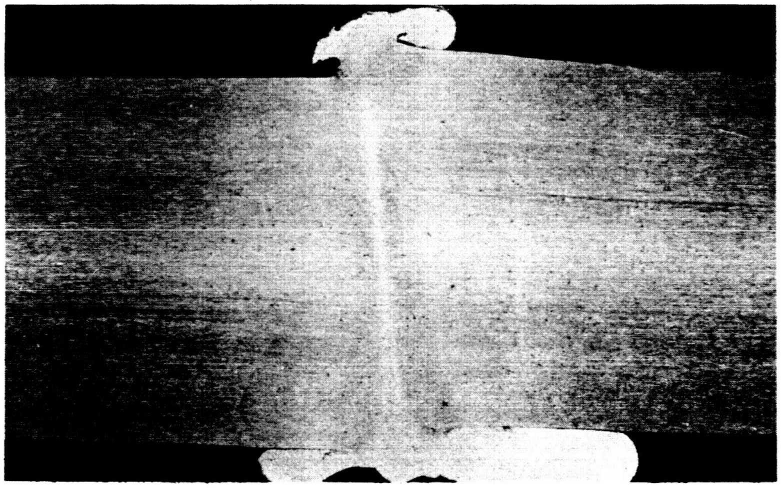
FIGURE I-1. STRIP GUIDING SYSTEM FOR WELDING EXPERIMENTS WITH AA2014-T6 ALUMINUM ALLOY

The strips enter the primary guide from an elevated position to help control strip buckling; then the outboard edges of the strips are horizontal between the primary guide and the squeeze rolls.



N97625

a. 5 Inches From the Start of the Weld (Underheated)



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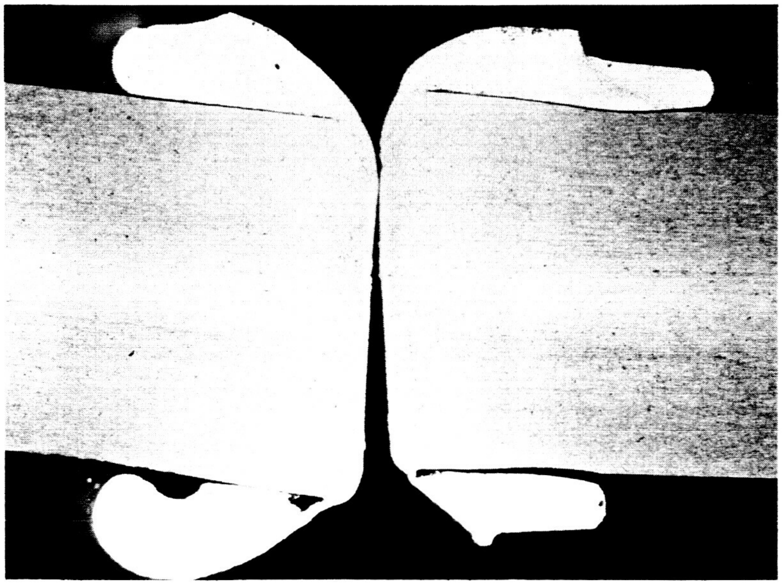
b. 15 Inches From the Start of the Weld (Suitable Power)



N97629

c. 25 Inches From the Start of the Weld (Overheated)

FIGURE I-2. TRANSVERSE CROSS SECTIONS FROM A HIGH-FREQUENCY RESISTANCE WELD MADE USING UPSLOPED WELDING POWER IN 0.093-INCH-THICK AA5456-4343 ALUMINUM ALLOY

TABLE I-3. SUMMARY OF RESULTS OF STUDIES WITH 2014-T6 ALUMINUM ALLOY[a]

Weld No.	Variable Studied	Variable Conditions	Joint Efficiency, per cent
FJ 1333[b]	Strip separation	125-mil gap - 320 volts[c]	47-54
FJ 1335[b]		125-mil gap - 335 volts[c]	47-60
FJ 1337		160-mil gap - 335 volts	48-50
FJ 1340	Upset distance at 90-fpm welding speed	134-mil upset - 350 volts	53
FJ 1337		170-mil upset - 335 volts	70
FJ 1345		204-mil upset - 340 volts	79
FJ 1357	Upset distance at 180-fpm welding speed	134-mil upset - 420 volts	69
FJ 1354		170-mil upset - 410 volts	71
FJ 1352		204-mil upset - 390 volts	80
FJ 1372		338-mil upset - 400 volts	82
FJ 1375	Upset distance at 360-fpm welding speed	204-mil upset - 550 volts	80
FJ 1384		238-mil upset - 530 volts	80
FJ 1362	Upset force	2400-lb force	70
FJ 1363		3000-lb force	60
FJ 1364		3000-lb force	61
FJ 1368		3750-lb force	66-80
FJ 1371	Minor speed variation	160 fpm	78-83
FJ 1387		180 fpm	75-83
FJ 1371	Contact position	45-mil offset } 390 volts	78-82
FJ 1390		100-mil offset } 390 volts	85
FJ 1372		45-mil offset } 400 volts	79-85
FJ 1391		100-mil offset } 400 volts	72-76
FJ 1373		45-mil offset } 410 volts	61-64
FJ 1392		100-mil offset } 410 volts	52-82
FJ 1392	Contact cooling	Contacts cooled	52-82
FJ 1393		Contacts not cooled	72-80
FJ 1352	Contact-to-squeeze roll distance	1.7 - inch distance	79-81
FJ 1395		2.55 - inch distance	75-83

(a) Detailed results are given in Table A-1, Appendix A.
(b) Arcing occurred in the Vee on welds noted. No arcing occurred on other welds.
(c) All voltages-wye connection.

(2) The effects of changing the welding power could not be clearly distinguished from changes made in other welding conditions. A 10-volt change in power had little effect on the joint mechanical properties, except when this change caused the weld to be distinctly over- or underheated. A 10-volt change in the power input would noticeably change the amount of weld reinforcement observed on the as-welded specimen.

(3) The properties of joints made at welding speeds of 160, 180, and 360 fpm were more constant than those of joints made at 90 fpm. The width of the weld heat-affected zone decreased as the speed was increased. A 13 per cent speed variation was found to have little effect on the joint properties.

(4) In general, joint efficiency increased as the upset distance was increased. Some cracking occurred in welds prepared under conditions that produced considerable upset. Most of this cracking was in the upset area and would not be of concern in the application of this process.

(5) The results of experiments in which a fixed upset force, without stops, was used indicated that this upsetting technique is less desirable than techniques in which the upset distance is carefully controlled. Upset forces of 2400 pounds or less produced weak welds. Upset forces greater than 3750 pounds caused "scissoring" of the strip. Within the range between these limits, satisfactory welds could be made with joint efficiencies ranging from 61 to 80 per cent.

(6) Changes in the contact position with respect to the edge caused only minor changes in weld strength when the contacts were positioned symmetrically. No welds could be made when the contact-to-edge distance was unequal (nonsymmetrical position).

(7) The results of welds made to study effects of contact coolant showed that welds made without coolant resulted in only slight changes in weld strength.

(8) Increasing the contact-to-squeeze roll centerline distance had little effect on the joint strength; however, this change did result in changing the width of the weld heat-affected zone. The welds made with the greater contact-to-squeeze roll centerline distance had a wider heat-affected zone.

The most important findings shown by the results of studies with the 2014-T6 alloy were

(1) The alloy is readily weldable by high-frequency resistance welding.

(2) Weld joint efficiencies in the range of 75 to 85 per cent can be obtained by this process.

(3) Although good joints can be made under various conditions, optimum results are obtained only when close control of the variables is effected.

The results of the experiments conducted with the 7179-T6 alloy are summarized in Table I-4 and in the following listing:

(1) Joint efficiencies of from 57 to 76 per cent were obtained at the various settings used in this study. The joint efficiencies of welds made at a power input level of 340 to 345 volts (wye) were the most consistent.

(2) No difficulty was experienced with arcing during the welding of this alloy. Visual examinations of the completed welds showed evidence of good appearance and uniform upset. There were no visible indications of weld defects.

(3) Metallographic examination disclosed that the welds in this alloy were more likely to crack than similar welds in the 2014 alloy. In some cases, cracks extended below the level of the sheet surfaces as shown in Figure I-3.

TABLE I-4. SUMMARY OF RESULTS OF STUDIES WITH 7179-T6 ALUMINUM ALLOY[a]

Weld No.	Power Setting, volts (wye)	Vee Width, mils	Joint Efficiency, per cent
FJ 1402	350	120	54-67
FJ 1403	340	120	69
FJ 1407	330	110	72
FJ 1408	340	110	56-76
FJ 1409	345	110	67

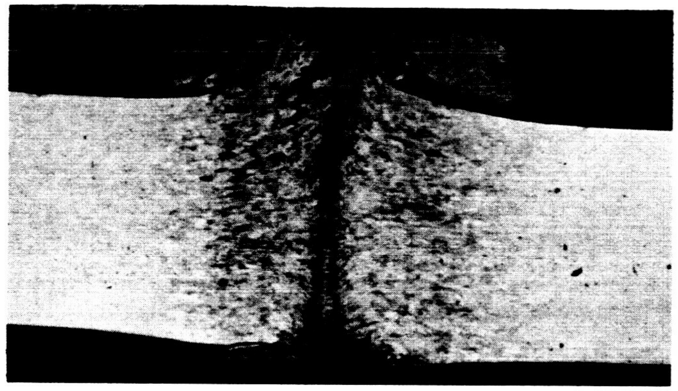
(a) Detailed results are given in Table A-2, Appendix A.

The most important findings shown by the results of studies with the 7179 alloy were

(1) The alloy is weldable by high-frequency resistance welding.

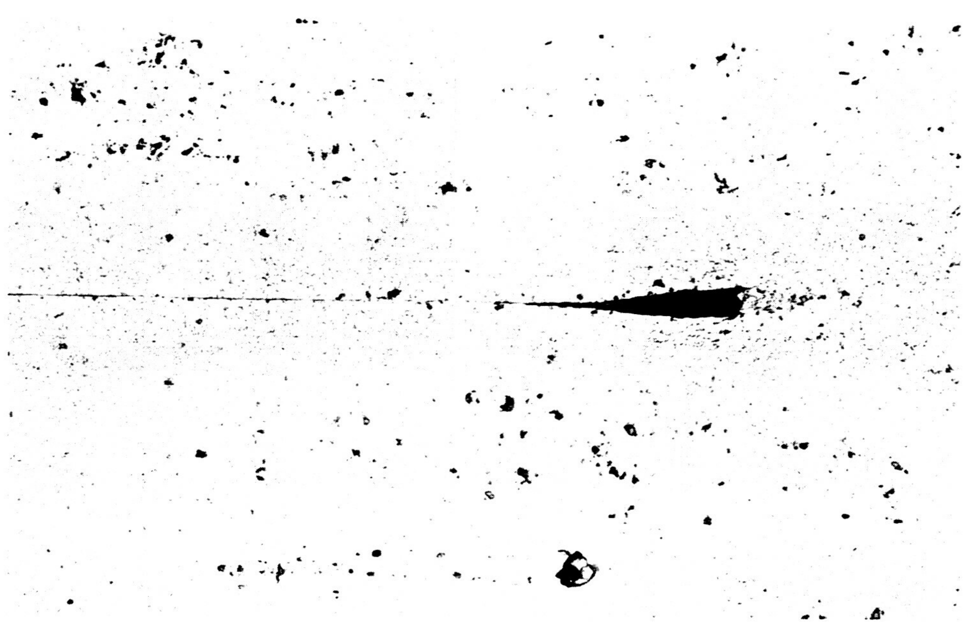
(2) Weld joint efficiencies averaging about 70 per cent were obtained by this process.

(3) Although good joints were made under these experimental conditions, it is believed that the optimum technique was not developed and that better results could be obtained by welding with a smaller upset distance.



Weld Number FJ 1402

FIGURE I-3. TRANSVERSE CROSS SECTIONS ILLUSTRATING CRACKING IN 7179-T6 ALLOY



H_2O-0.5% HF Etchant; Weld Number FJ 1236

FIGURE I-4. WELD DEFECT ATTRIBUTED TO ARCING IN A HIGH-FREQUENCY RESISTANCE WELD IN 0.093-INCH-THICK AA5456-H343 ALUMINUM ALLOY

View shown is the polished upper surface of the strip.

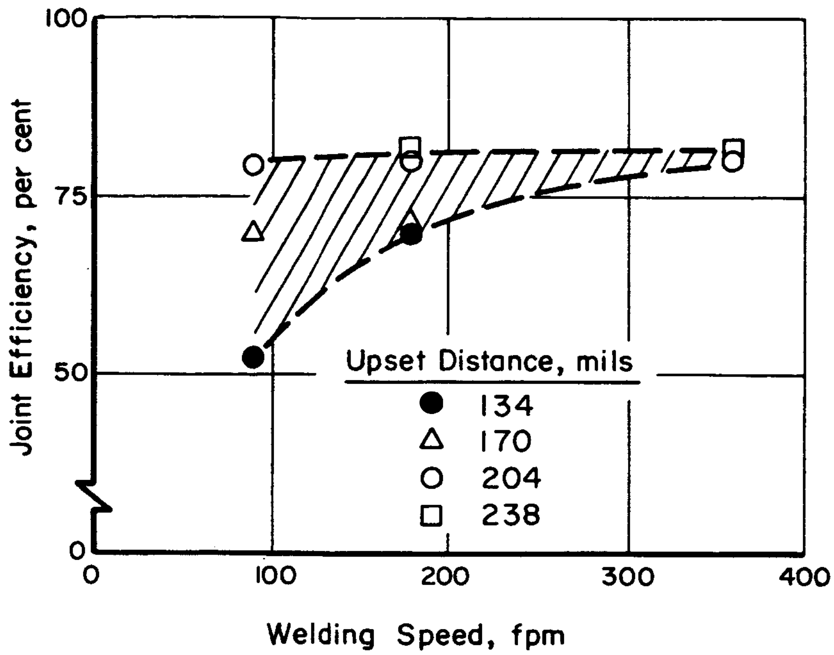
Discussion

Experimental difficulty was initially encountered in attempts to translate previously determined welding conditions to aluminum alloys. There was a tendency for arcing to occur at the initial conditions used to weld aluminum. In attempting to get around this problem a second difficulty was encountered. This was in guiding the aluminum strips to form a vee with a wide separation. Use of a combination of twisting and elevating the strips was most successful in solving both problems. With this guiding system, the outboard edges of the strips were guided through the weld station without any change in elevation between the primary guide and the squeeze-roll centerline. The strips were elevated upstream from the primary guide to improve positioning of the strip as it passed through the mill. With this guiding method buckling of the strips at the welding station was avoided.

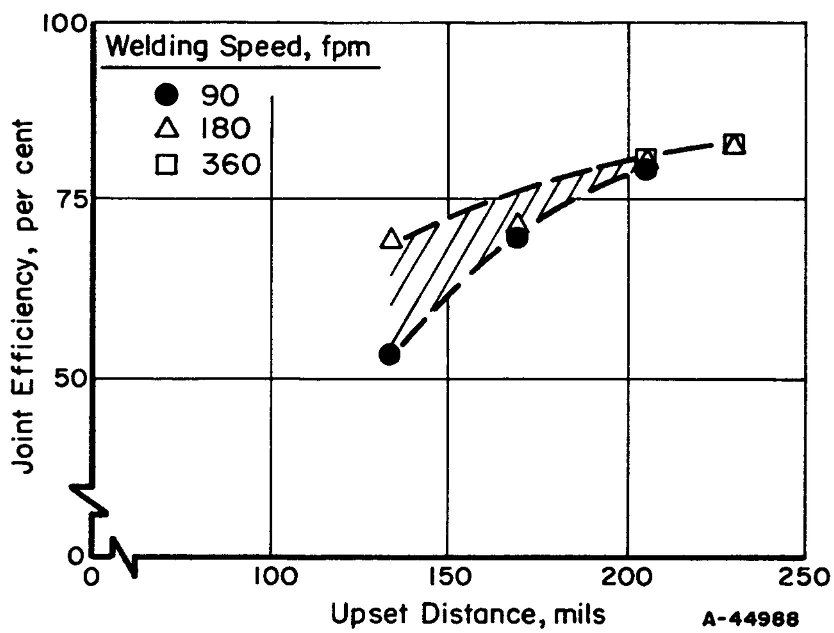
During the work to overcome the arcing problem, 5456-H343 alloy welds were evaluated by bend tests of as-welded specimens and by metallographic examinations. The bend specimens broke easily along the weld, and examinations of the fracture surfaces showed incomplete bonding and the presence of bright smooth areas resembling cold shuts. The number of smooth areas present in the fracture surfaces increased as the power was increased. Since the amount of arcing also increased when the power was increased, the smooth areas appeared to be related to arcing that occurred in the vee during welding. Fracture surfaces of welds made under conditions where arcing did not occur were free of the smooth areas. Further evidence of the effects of arcing is shown in Figure I-4. This figure is a longitudinal section of a defect that probably occurred because of arcing. At the left of the main defect there is evidence of the original interfaces, indicating that welding conditions were not satisfactory before the defect was created. A portion of the weld at the right of the defect shows a good weld. An important conclusion from the study of 5456-H343 alloy was that only a very narrow power range appeared suitable for welding the aluminum alloys.

The initial work with the 2014-T6 alloy confirmed the tentative conclusions formed regarding the weld characteristics of aluminum alloys in earlier studies. Arcing also occurred at the vee when welding this alloy with a narrow vee opening. Attempts to relate the arcing behavior to contact placement showed that the contact position had no effect on the arcing characteristics. Arcing was completely eliminated by increasing the strip separation. It is important that arcing be prevented since it will cause nonuniform heating of the strip edges and inconsistent welds. A wider vee opening resulted in welds that were of more uniform visual appearance.

The individual effects of power level, upset distance, and speed cannot be studied separately. Thus the evaluation of these three variables was based on interrelated experiments. Several values of upset distance were studied at each welding speed. The power level was adjusted to produce welds of satisfactory appearance for each combination of upset distance and speed. Relationships established in this study are shown graphically in Figure I-5. It can be seen from this figure that changes in the welding speed do not appreciably change the joint efficiency at large upset distances. However, the heat-affected zone becomes narrower at the higher welding speeds. This observation suggests that perhaps a maximum joint efficiency is obtainable in the 2014 alloy by high-frequency resistance welding and that further decreases in the weld and heat-affected zone width do not result in additional improvement of the joint efficiency. With small amounts of upset, joint efficiency increases very rapidly as the welding speed increases.



a. Joint Efficiency Versus Welding Speed



b. Joint Efficiency Versus Upset Distance

FIGURE I-5. RELATIONSHIPS BETWEEN WELD JOINT EFFICIENCY AND WELDING SPEED ON UPSET DISTANCE

Power level was adjusted with welding speed.

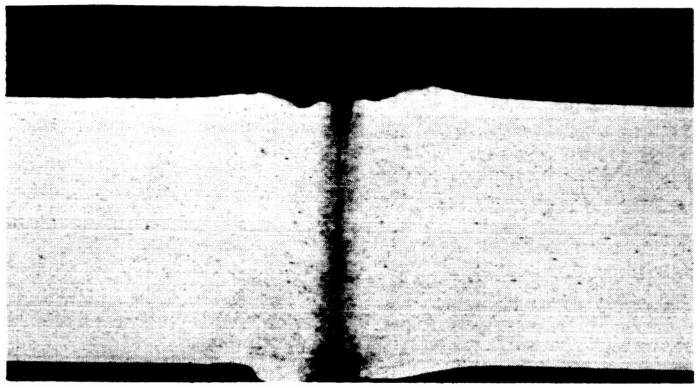
As expected, increasing the upset distance increased the distortion at the weld interface as shown in Figure I-6. Also, as the upset distance was increased, cracking was produced in the upset material. This cracking extended below the level of the material that would normally be removed from a high-frequency resistance weld only at the very highest upset distances. It appears that the upset distance should be limited to the minimum value needed to produce a weld with a good joint efficiency. Further increases in the upset distance may result in decreasing the reliability of joints made by this process.

As mentioned in the "Results" section, the use of a fixed upset force was not as satisfactory as controlling the upset distance. The strength of welds made employing a fixed upset force varied rather widely along the length of the weld. Also, there appeared to be a greater tendency for cast metal to be trapped in the weld zone when using this technique under the conditions evaluated as shown in Figure I-7. A fixed upset force does not provide good control of the lateral position of the vee apex. Any shift in the lateral position of the vee apex may change the heating characteristics along the edges of the vee and lead to nonuniform welds.

Welds made with different contact-to-edge distances showed very little difference in joint efficiency. However, when a nonsymmetrical contact-to-edge distance was employed, good welds were not made. Nonsymmetrical positioning of the contacts will produce an unequal resistance in the legs of the vee and result in unequal heating of the opposite edges of the strip. It appeared that this was the case and that one strip edge was underheated while the opposite edge was overheated. The use of nonsymmetrical contact positioning would be quite helpful in making dissimilar metal joints, since the heat generated on the opposite sides of the vee could be balanced (in materials with different resistances) by this technique.

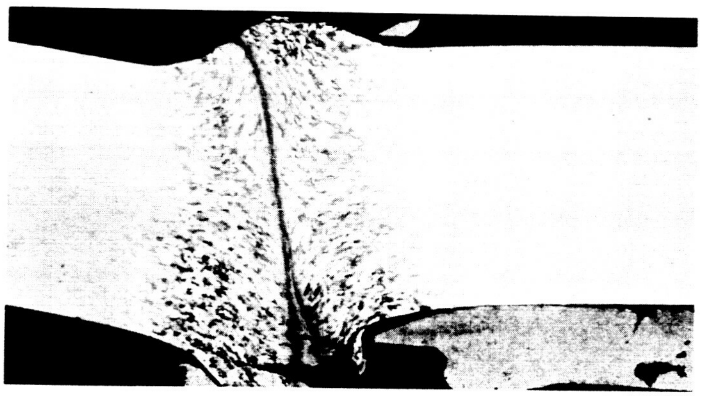
Changing the contact-to-squeeze roll centerline distance was found to have the opposite effect on the width of the heat-affected zone as changing the welding speed. The width of the weld heat-affected zone becomes greater when either the speed is decreased or the contact-to-squeeze roll centerline distance is increased. This similarity is expected since the effects in either case are to change the time during which the edges are heated. One advantage that can be made of this interrelationship is that a change in one of these variables can be used to compensate for changes in the other variable.

Although the welding study of the 7179-T6 alloy was not as extensive as that of the 2014-T6 alloy, it provided valuable information of the welding characteristics of this alloy. The most important difference found between the two alloys was the somewhat greater tendency of the 7179-T6 alloy to exhibit cracks after welding. The appearance of these cracks was shown in Figure I-3. Those cracks at the top of each weld tend to follow the metal flow lines, and probably resulted from using an upset distance that was too high. Cracks at the bottom of the welds are believed to be the result of buckling or dishing of the welded strip at a point downstream from the welding station. Cracking at both locations can probably be eliminated by further studies to establish an optimum upset distance that will still provide high strength and by containing the strip better as it leaves the welding station.



530

a. Weld Number FJ 1357; Preset Upset Distance 134 Mils

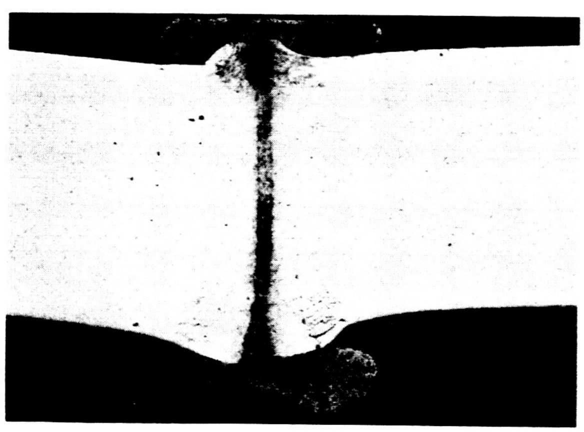


534

b. Weld Number FJ 1372; Preset Upset Distance 238 Mils

FIGURE I-6. TRANSVERSE CROSS SECTIONS OF HIGH-FREQUENCY RESISTANCE WELDS IN 0.068-INCH-THICK AA2014-T6 ALUMINUM ALLOY SHOWING THE EFFECTS OF INCREASING THE PRESET UPSET DISTANCE

Welding speed was 160 fpm.



532

Weld Number FJ 1363

FIGURE I-7. CAST METAL TRAPPED IN A 2014-T6 WELD MADE USING A FIXED UPSET FORCE - 3000 LB FORCE

STAINLESS STEELS

Welding studies were made with two grades of stainless steel in two thicknesses as indicated below:

(1) AISI 310 - Full hard, 0.114 inch thick

(2) AISI 310 - Full hard, 0.072 inch thick

(3) AISI 301 - Full hard, 0.072 inch thick.

Studies conducted with each alloy and thickness will be treated separately in the following sections, since the experimental conditions employed were related to the alloy grade and thickness. Procedures which were used in welding the stainless steels, the results obtained, and discussion of these results are covered in the following sections.

Procedures

The procedures used in the studies made with the thicker AISI 310 stainless steels were as follows. The strips were guided into the welding station by twisting, elevating, and forcibly separating each strip. Welds were made with this guiding system to establish the effects of a number of welding variables on the weld strength. The effect of using a fixed upset force without stops was evaluated by varying the upset force from 2250 to 6750 pounds. These welds were made at a power setting of 405 volts (delta) and a welding speed of 180 fpm. The effect of varying the upset distance was evaluated by changing this distance within the range from 37 to 137 mils. These welds were made at a power setting of 515 volts (wye) or 330 volts (delta) and a welding speed of 90 fpm. The effects of variations in the power input were evaluated by making welds with input voltages of 325 and 360 volts (delta) and 550 volts (wye). These welds were made at a preset upset distance of 97 mils and a welding speed of 90 fpm. The effects of changing the contact-to-squeeze roll distance was evaluated by changing this distance from 3.0 (standard condition) to 2.3 inch. These welds were made with a 97-mil upset and a welding speed of 90 fpm. The effects of changing the welding speed was evaluated by changing from 90 to 40 fpm. These welds were made at power inputs ranging from 350 to 490 volts (wye), at a 97-mil upset distance. Detailed welding conditions are given in Table A-3, Appendix A.

Procedures used in welding the 0.072-inch-thick AISI 310 stainless steel were as follows. Welds in this material were made using a vee formed in the same manner that was used for the 2014-T6 aluminum alloy. The vee opening of 110 mils measured 1.7 inch from the squeeze-roll centerline, and grooved squeeze rolls were used. The radial angle under the electrical contacts was 15 degrees. All welds were made employing a fixed upset force without stops and a protective atmosphere around the weld station. The protective atmosphere was obtained by covering the weld station, the primary guide, and the postweld guide with polyethylene sheet. Two gas lines were positioned to flood the top and bottom of the vee. The shielding gas was supplied by these lines at a flow rate of 250 cfh. The shielding system was purged for at least 10 minutes before the start of each weld. Additional precautions were taken when the protective atmosphere was employed. These included wiping the strip with acetone prior to welding, wire brushing the strip edges as required, and not using coolant for the contact shoes. Two welds were made to establish the effects of changing the power input of welds in this material. One was made at 510 volts (wye), and the other at 525 volts (wye). A welding speed of 250 fpm and an upset force of 6000 pounds were employed. Detailed welding conditions are given in Table A-5, Appendix A.

Welding studies with the 0.072-inch-thick AISI 301 stainless steel also were made with the guiding arrangement used for the thinner 310 stainless steel and the 2014-T6 aluminum alloy. All welds in this alloy were made using a fixed upset force and the helium atmosphere previously described. Welds were made at a welding speed of 250 fpm, with the contact placed 1.7 inch from the squeeze-roll centerline. Each contact was 30 mils from the edges of the strip. The effects of variation in upset force and power level were evaluated. Upset forces of 4125, 6000, and 7500 pounds were used. Power settings ranged from 485 volts to 550 volts (wye). Detailed welding conditions are given in Table A-6, Appendix A.

Results

Results of the experiments conducted with the 0.114-inch-thick AISI 310 stainless steel are summarized in Table I-5 and the following listing:

(1) Welds with the highest joint efficiencies were obtained with a fixed upset force. However, welds were obtained with only slightly lower joint efficiencies using a constant preset upset distance.

(2) Increasing the preset upset distance resulted in an increase in the strength of the weld when the other variables were held constant. Welds made with a constant preset upset distance contained unbonded areas at the bottom of the weld.

(3) Weld strength was affected by the power input. Of the three power levels investigated, the medium power input produced a weld with the highest weld strength.

(4) Weld joint efficiency was increased by decreasing the contact-to-squeeze roll centerline distance.

(5) Decreasing the weld speed resulted in a decrease in weld joint efficiency. Some arcing was observed during welding at a slow rate of speed. Apparent unbonded areas were observed on the fracture surfaces of these welds.

The results of experiments conducted with the 0.072-inch-thick AISI 310 stainless steel are summarized in the following sentences. Detailed results are given in Table A-5, Appendix A. Welds with uniform visual appearance along the weld length were obtained, but there was more weld reinforcement at the top of the welds than at the bottom. Examination also disclosed that the appearance of the upset was good. No arcing was observed during any of the experiments. Variation of the power setting in the range conducted for this study did not appreciably affect the strength of the weld. Joint efficiencies of about 85 per cent were obtained for all experimental conditions. Joint efficiency was very consistent, with the total range being only from 84 to 86 per cent, even when the power input was changed by as much as 15 volts (wye).

TABLE I-5. SUMMARY OF RESULTS OF STUDIES WITH AISI-310 STAINLESS STEEL[a]

(0. 114 inch thick)

Weld No.	Variable Studied	Variable Conditions	Joint Efficiency, per cent
FJ 613	Upset force at	4500 lb - 405 volts (delta)	83
FJ 617	180 fpm	6750 lb - 405 volts (delta)	83-89
FJ 619	Power input at	360 volts (delta)	46-58
FJ 620	90 fpm and	325 volts (delta)	58-69
FJ 621	97-mil upset	515 volts (wye)	49-57
FJ 624	Upset distance at	137-mil upset - 515 volts (wye)	80-84
FJ 623	90 fpm	117-mil upset - 515 volts (wye)	55-69
FJ 622		97-mil upset - 515 volts (wye)	59-61
FJ 625		37-mil upset - 330 volts (delta)	45-89
FJ 622	Contact-to-squeeze roll distance at	3. 0-inch distance - 515 volts (wye)	59-61
FJ 627	90 fpm	2. 3-inch distance - 490 volts (wye)	82-86
FJ 626		2. 3-inch distance - 420 volts (wye)	36-58
FJ 627	Welding speed at	90 fpm - 490 volts (wye)	82-86
FJ 628	97-mil upset	40 fpm - 350 volts (wye)	72-73
FJ 629		40 fpm - 370 volts (wye)	66-78
FJ 630		40 fpm - 370 volts (wye)	70-74

(a) Detailed results are given in Tables A-3 and A-4, Appendix A.

The results of the experiments conducted with the 0.072-inch-thick AISI 301 stainless steel are summarized in Table I-6 and below. The welds obtained were uniform in visual appearance. Again, more weld reinforcement was present on the top of the strips than on the bottom. No arcing occurred in these experiments. There was little difference in the joint efficiencies of welds made at different power settings and 4125-pound upset force. The joint efficiencies of these welds averaged about 70 per cent. Twenty volts (wye) change in the power setting did not affect the weld strength. A slight increase in the joint efficiency was obtained by increasing the upset force to 6000 pounds. Variation in the power setting at this upset force appeared to have some effect on the joint efficiency. The weld joint efficiency was slightly higher at the lower power setting. A further increase in the upset force to 7500 pounds resulted in a poor weld. The upper portion of this weld was not bonded as shown in Figure I-8. Mechanical-property tests were not made on this weld.

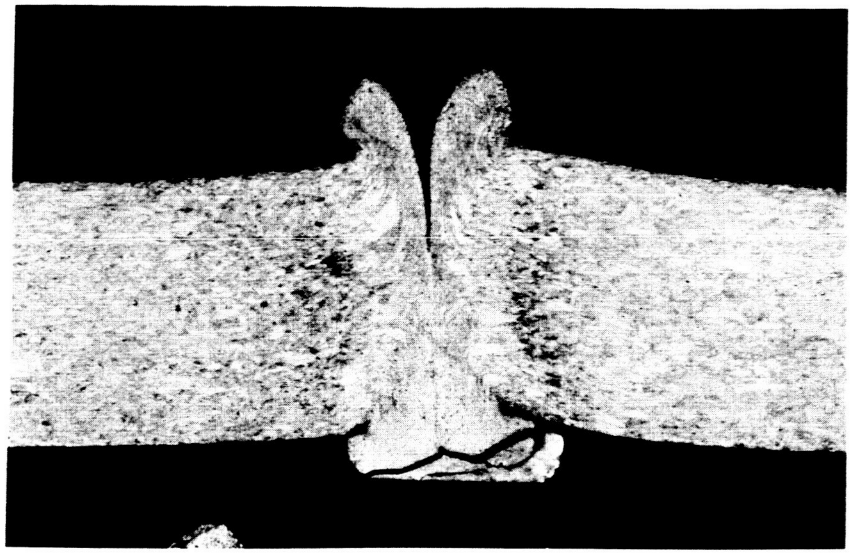


FIGURE I-8. TRANSVERSE CROSS SECTION OF A WELD IN 0.072-INCH-THICK AISI 301 STAINLESS STEEL SHOWING THE EFFECTS OF EXCESS UPSET FORCE

The most important findings shown by the results of studies with the stainless steels were

(1) Full-hard stainless steels are readily weldable by high-frequency resistance welding.

(2) Weld joint efficiencies averaging about 70 to 80 per cent were obtained by this process.

(3) The stainless steels investigated appeared much less sensitive to changes in the welding conditions than was found to be the case for aluminum alloys.

TABLE I-6. SUMMARY OF RESULTS OF STUDIES WITH AISI 301 STAINLESS STEEL[a]

(0.072 inch thick)

Weld No.	Variable Studied	Variable Conditions	Joint Efficiency, per cent
FJ 705	Power input at	550 volts (wye)	70
FJ 707	4125-lb upset	540 volts (wye)	69-71
FJ 706	force	530 volts (wye)	69-70
FJ 708	Power input at	540 volts (wye)	73-75
FJ 709	6000-lb upset	525 volts (wye)	72-76
FJ 710	force	515 volts (wye)	69-72
FJ 711		500 volts (wye)	77
FJ 712		485 volts (wye)	74-79

(a) Detailed results are given in Table A-6, Appendix A.

Discussion

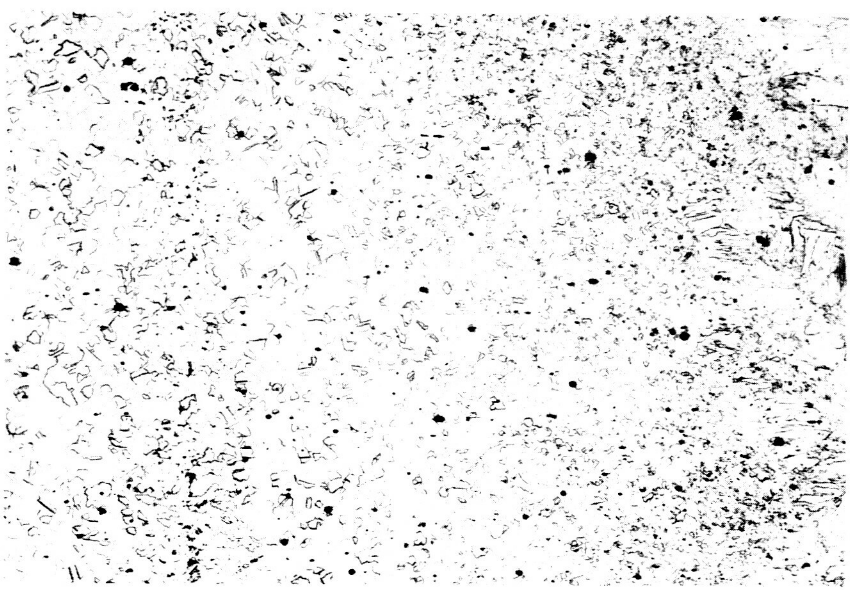
Much of the evaluation of high-frequency resistance welds in the stainless steel alloys had to be based on the observations made during metallographic examination, since it was generally found that changes in the welding conditions had little effect on the joint strengths.

Metallographic sections of a weld produced to evaluate the effects of upset force are shown in Figure I-9. This weld was made with 4500 pounds of upset force and contained cast metal at the bottom of the weld. The cast metal extends from the bottom of the weld into the weld faying plane. However, despite the presence of some cast metal in this weld, the joint had the excellent joint efficiency of 83 per cent. A small defect is also present in this weld. This type of defect is believed to be caused by arcing in the vee during welding. Reference to the photomacrograph shows that there is more evidence of heating at the bottom of the weld than there is at the top. This additional heating at the bottom edge was probably caused by the proximity effect. The photomicrograph in Figure I-9 shows a typical microstructure of high-frequency resistance welds made in full-hard stainless steel. Examination of the structure shown indicates that there is fine-grained recrystallized metal near the bond line, then an area of mixed small recrystallized grains, followed by cold-worked metal that separates the cold-worked parent material from the weld zone.

Similar evidence of overheating at the bottom of the weld was obtained in examinations of the thinner gage AISI 310 stainless steel weldments. Figure I-10 shows a weld in this material illustrating this and several other features. Examination of this figure shows that the weld reinforcement at the top of the weld consists mostly of upset, that is, metal which was plastically extruded from the weld while the metal was hot. The bottom of the weld also contains some upset, but beneath this upset there is an area of cast metal. Again, this observation seems to confirm the additional heating caused by

20X N97352

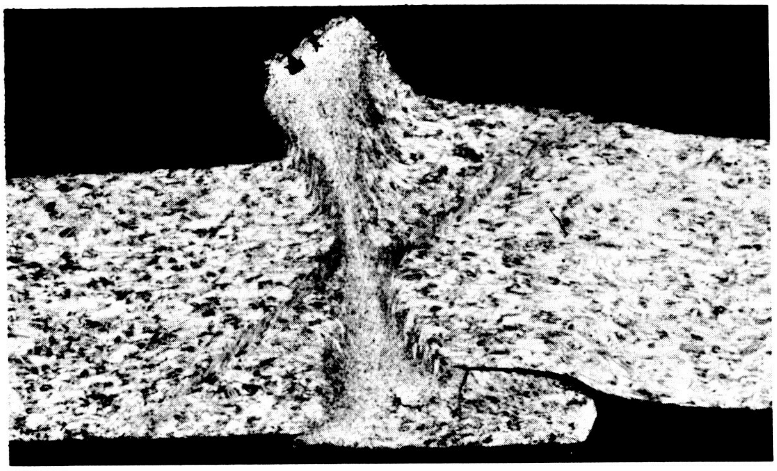
Glyceregia Etch



100X N96652

Glyceregia Etch; Weld Number FJ 613

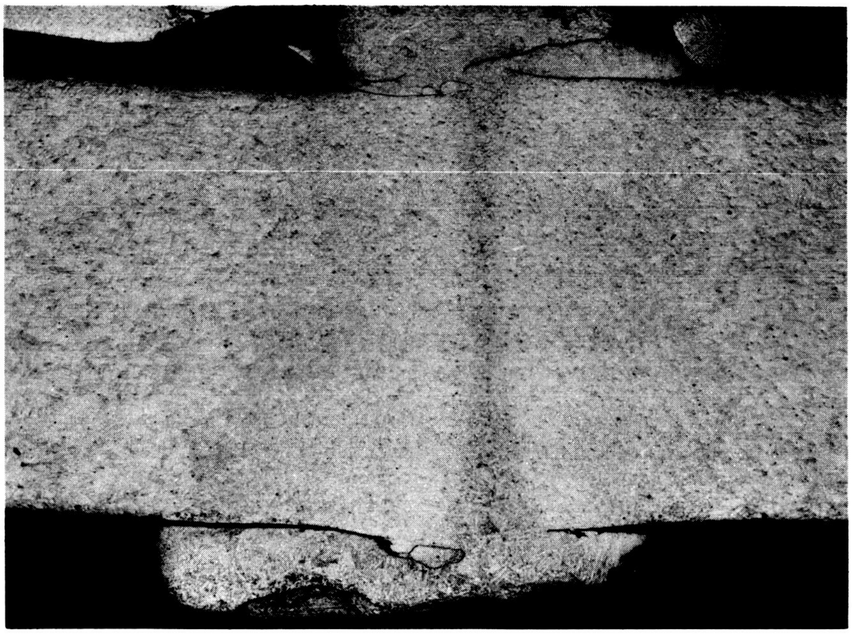
FIGURE I-9. TRANSVERSE SECTIONS OF HIGH-FREQUENCY RESISTANCE WELDS IN 0.114-INCH-THICK AISI 310 FULL-HARD STAINLESS STEEL



20X 547

Glyceregia Etch; Weld Number FJ 1001

FIGURE I-10. TRANSVERSE CROSS SECTION OF HIGH-FREQUENCY RESISTANCE WELDS IN 0.072-INCH-THICK AISI 310 STAINLESS STEEL



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Glyceregia Etch; Weld Number FJ 629

FIGURE I-11. TRANSVERSE CROSS SECTION OF HIGH-FREQUENCY RESISTANCE WELD MADE USING A SLOW WELDING SPEED OF 40 FEET PER MINUTE IN 0.114-INCH-THICK AISI 310 STAINLESS STEEL the proximity effect. Also shown in Figure I-10 is a line of heavily plastically deformed material extending from the upper right to the lower lefthand corner. This line is at an angle of approximately 45 degrees to the bottom of the strip. An analysis of the compressive forces present in the strip showed that the maximum shear stress occurs along a similar angle. Therefore, it appears that the compressive force on the strips caused the material to flow along the line of maximum shear stress intensity or at 45 degrees to the weld's cross-sectional area. The edges of the strip that were used in this weld had been rolled square before welding. Examination of these edges in the as-received material disclosed slip lines at an angle of 45 degrees. Although it appears that the welding upset force made some contribution to the formation of the plastically deformed material along the 45-degree line, it is likely that this deformation was initiated during the square-rolling operation. Slip lines in the as-welded specimen were wider than those in the as-received material. Only one slip line could be observed in the as-welded material, while two slip lines could be observed in the as-received material.

Metallographic examinations also disclosed the presence of a small crack near the surface of the weld made at the largest preset upset distance during the evaluation of the effect of variations in this distance. The weld made at the other extreme (lowest preset upset distance) contained some cast metal in the weld area. These observations indicate that the upset distance must be controlled within well-defined limits when a preset-upset-distance technique is employed. Cast metal was also found at the weld interface in welds made at a low welding speed. This is shown by the photomacrograph exhibited in Figure I-11. Except for the presence of this cast metal and cracks in the upset which would normally be removed, this weld exhibits the features of a good high-frequency resistance weld.

Metallographic techniques also were used to evaluate the welds made at 7500-pound upset force which contained an unwelded band at the top. A section through this weld was shown in Figure I-8. The unbonded area at the top is obvious. It is believed that the upper surfaces of this weld did not bond because the upset force was excessive, thus ejecting all of the hot metal from the top area of the weld and leaving only cold surfaces to put together.

Metallographic sections were also employed to determine the width of the weld heat-affected zone of selected weld joints. Measurement of this width showed that decreasing the contact-to-squeeze roll centerline distance from 3 to 2.3 inches produced a corresponding decrease in the heat-affected zone width of from 0.07 to 0.06 inch. Decreasing the welding speed from 90 to 40 fpm was found to increase the heat-affected zone width from 0.06 to 0.10 inch. A good correlation between the heat-affected zone width and the joint efficiency was found in this study. Welds that showed the smallest heat-affected zone width exhibited the highest joint efficiencies.

TITANIUM ALLOYS

The weldability of titanium alloys was determined by studies on 0.063-inch-thick Ti-6Al-4V alloy. This was the only titanium alloy readily available and was in the solution-annealed condition. Initial welding conditions were selected on the basis of results previously obtained with aluminum alloys and stainless steels.

Procedures

A few variations in welding conditions were explored with the titanium alloys. The guiding system employed involved twisting and elevating the strips as shown in the system used for 2014-T6 aluminum. All welds were made using a preset upset distance of either 189 or 204 mils. Welding speeds of 160 and 250 fpm were evaluated. Electrical contacts were positioned 1.7 inches from the squeeze-roll centerline, and 15 mils from the strip edges. Strip separation at the contact point was 150 mils. All welds were made using the protective atmosphere system previously described. The contact shoes were 3/8-inch-wide, high-conductivity Elkaloy A. Detailed welding conditions are given in Table A-7, Appendix A.

Results

Results of the experiments conducted with the Ti-6Al-4V alloys are summarized in Table I-7 and below.

TABLE I-7. SUMMARY OF RESULTS OF STUDIES WITH Ti-6Al-4V ALLOY[(a)]

Weld No.	Variable Studied	Variable Conditions	Joint Efficiency, %
FJ1602	Power input at 160 fpm	350 volts (wye)	100
FJ1603	and 189-mil upset	360 volts (wye)	100
FJ1604	distance	370 volts (wye)	100
FJ1605	Welding speed at	160 fpm	68-100
FJ1607	205-mil upset	250 fpm	100
	distance		

(a) Detailed results are given in Table A-7, Appendix A.

All welds had good visual appearance and upset. No arcing was observed during the welding of this alloy. The joint efficiency of all except one weld was 100 per cent, based on the starting base-metal strength. Welds in this alloy appeared to be formed readily.

Important findings shown by the results of studies with the titanium alloy were

(1) The alloy is weldable by high-frequency resistance welding.

(2) Weld joint efficiencies of 100 per cent were obtained in these experiments.

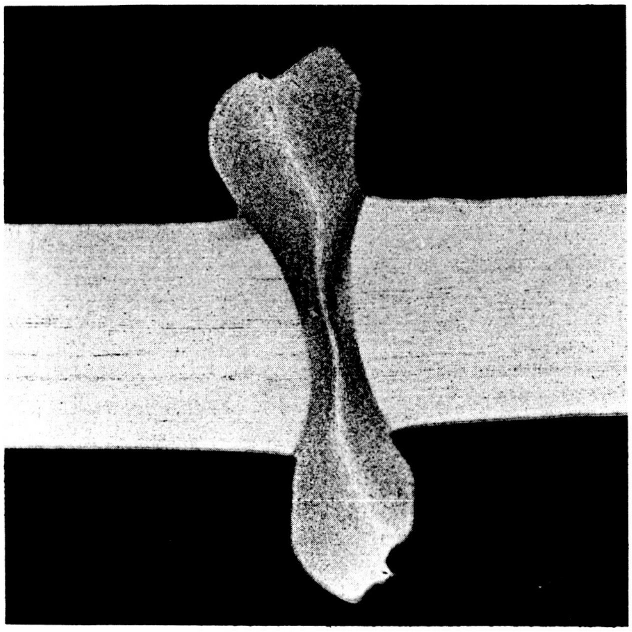
Discussion

Since the majority of the welds in the titanium alloy exhibited 100 per cent joint efficiency, the effects of changing the welding conditions were not as apparent as for the other materials studied. Welds made at an upset distance of 189 mils exhibited a decrease in the total heat-affected-zone width as the power setting was increased. This behavior appears to be related to the ease with which the metal in the weld area would flow during upset. Increasing the power level resulted in an increase in the tendency for good flow during upsetting, and actually produced a narrower weld zone in contrast to what might be expected. Apparently, the stops limiting the upset distance were not reached on all welds, as evidenced by this behavior. Thus, the upset on some of the titanium welds was controlled by the fixed upset force (4125 lb). The weld reinforcement of all of these welds was predominantly metal that was heated into the plastic range and was then squeezed from the weld interface.

The only weld evaluated that exhibited a joint efficiency lower than 100 per cent in some areas was made with an upset distance of 205 mils. The low joint efficiency of this weld may have been caused by inadequate power.

Figure I-12 shows a typical transverse cross section of a high-frequency resistance weld in the titanium alloy. As shown in this figure, the appearance of the weld reinforcement was somewhat unusual. In general, the amount of weld reinforcement obtained in welding the titanium alloy was much greater than the amount of upset obtained with the other program materials. Additional studies of other welding conditions incorporating smaller upset distances might produce upsets that are considered more characteristic of the high-frequency resistance welding process.

The yield strength of the as-received titanium alloy was 129.0 ksi. The yield strength of all the welds except FJ 1603 was considerably less than this value. The yield strength of Weld FJ 1603 was within 97 per cent of the yield strength of the parent metal, which shows high yield-strength efficiencies can be developed for this process. The elongation of Weld FJ 1603 was the same as the elongation of the parent metal, and the elongation of the other welds were close to the elongations of the parent material.



20X 1241

Flick's Etch; Weld Number FJ 1602;
100 Per Cent Joint Efficiency

FIGURE I-12. TRANSVERSE CROSS SECTION OF A HIGH-FREQUENCY RESISTANCE WELD IN 0.063-INCH-THICK Ti-6Al-4V ALLOY

PHASE II

Evaluate the information from Phase I, selecting those materials offering promise of process compatibility and verifying extension of the process to the making of longitudinal and circumferential joints in a typical range of space-vehicle thickness and dimensions.

PHASE II. PROCESS ADAPTABILITY

The object of Phase II was to select the materials that offered promise of process compatibility on the basis of information obtained in Phase I and verify the extension of the process to the making of longitudinal and circumferential joints in a typical range of space-vehicle thicknesses and dimensions. In Phase I a large number of welds were made to establish the weldability and mechanical properties of the program materials. In making the Phase I evaluations, it was necessary to establish the effects and interrelationships of important material and basic process variables as related to weld quality. Then the results obtained during the Phase I studies were used to establish the materials that were most readily weldable. The most weldable materials then were used to study the process for use with thicknesses that meet the strength requirements of space launch vehicles.

The characteristics and properties of welds obtained with the program materials were described in this report under Phase I. In order to establish the materials that were comparible with the process, and to establish the thickness range of usefulness for the process, it is necessary to briefly review some of the work done and results obtained during Phase I.

One objective of Phase II of the present program was to select the materials that offer promise of process compatibility on the basis of the results of Phase I. As was described earlier in this report, low-carbon steel was welded initially and satisfactory welds were obtained using a wide range of welding conditions with several strip-guide tooling arrangements. After satisfactory welds were produced and experimental procedures developed with low-carbon steel, welding studies were conducted using the program materials. The materials and material thicknesses that were welded during the study are reported in Table II-1. Welding conditions and guiding arrangements required to weld some of the program materials were extremely limited. With these materials it was necessary to investigate a wide range of welding variables with several guiding arrangements to establish a suitable range of welding conditions. Then, many welds were made and evaluated to establish weldability and mechanical properties.

COMPATIBILITY OF MATERIALS WITH THE HIGH-FREQUENCY RESISTANCE WELDING PROCESS

Numerous factors must be considered to establish whether a material is compatible with the high-frequency resistance welding process or whether the process is adaptable to welding a specific material. With the materials included in this study, the ability to form the proper vee configuration for welding without arcing was of extreme importance. The control of the vee for welding of strips was difficult to achieve early in the program, and investigations were made to establish proper control of this factor. After control of the vee was established, the high-frequency welding process was capable of welding all of the materials with which a suitable vee could be formed.

On the basis of the studies conducted and results obtained during the program, the high-frequency resistance welding process is capable of welding each material that was included in the study with varying degrees of success. As stated earlier,

TABLE II-1. REVIEW OF MATERIALS AND MATERIAL THICKNESSES WELDED IN THE HIGH-FREQUENCY RESISTANCE WELDING PROGRAM

Material Designation	Thickness Welded, in.
Stainless Steels	
AISI 310 stainless steel, full hard	0.114
	0.072
AISI 301 stainless steel, full hard	0.072
Aluminum Alloys	
AA1100-H14	0.093
AA2014-T6	0.068
AA5456-H343	0.093
AA7179-T6	0.062
Titanium Alloys	
Ti-6Al-4V	0.063
Steel	
AISI C1010	0.109

low-carbon steel was welded using a wide range of welding conditions. On the basis of welding results with steel, the conditions for welding the aluminum alloys and the titanium-6 aluminum-4 vanadium alloy are within a very narrow range. However, this is true of many welding processes. High joint efficiencies were achieved with these alloys in strength tests. The stainless steels were readily weldable and high joint strengths and joint efficiencies were obtained.

Weld-strength test results obtained with the materials welded during this program are given in Table II-2. These results show that high strength and high joint efficiency were obtained with each alloy for which a suitable vee configuration could be provided. Metallographic examination of transverse cross sections also showed that with proper welding conditions, sound welds were made. These welds had several desirable characteristics including little evidence of entrapped cast metal, narrow heat-affected zones, and freedom from cracks and porosity. With the stainless steel alloys, sound welds were made with a relatively wide range of welding conditions. With the aluminum alloys, however, the range of welding conditions required to produce good welds was very limited. High-strength test results were obtained with the aluminum alloys but cracking was observed in the upset portion of the high-strength welds. This cracking was usually in the upset area that would be removed during normal weld cleanup. When welding conditions were modified to reduce the amount of upset to eliminate cracking, the strengths of the welds decreased. The strengths obtained with titanium alloy weldments also were high. However, there were indications of low ductility when sample coupons were sheared from the completed welds.

On the basis of the results obtained so far in this program, the stainless steel alloys were most readily adapted to the process. The major factors leading to the selection of the stainless steels for further study were

(1) The high joint efficiencies produced with the process

(2) Freedom from any weld defects

(3) The reasonably wide range of welding conditions within which high-strength welds could be produced.

EXTENSION OF PROCESS TO VARIOUS THICKNESSES

Another objective of Phase II of the study was to verify extension of the process to the making of longitudinal and circumferential joints in a typical range of space-vehicle thicknesses and dimensions. To achieve this objective, it was necessary to prepare and evaluate welds in various thicknesses of the selected materials and to evaluate the tooling and strip guiding arrangements simultaneously. The needed studies were initiated using AISI 310 stainless steel in the full-hard condition. Welds were completed in two thicknesses of this stainless steel, 0.072 and 0.114 inch. The welding results obtained with AISI 301 stainless steel were similar to the results obtained with the 310 stainless and both materials are considered to be similar insofar as high-frequency resistance welding is concerned. The welding results obtained with the same thickness of each material (0.072 inch) were similar. On this basis, the behavior of other similar thicknesses of these stainless steels would not be expected to be widely different.

TABLE II-2. SUMMARY OF THE HIGHEST WELD-JOINT EFFICIENCIES OBTAINED AND THE WELDING CONDITIONS USED FOR HIGH-FREQUENCY RESISTANCE WELDS IN VARIOUS MATERIALS

Weld No.	Ultimate Tensile Strength, ksi	Yield Strength (0.2% Offset), ksi	Elongation, per cent in 1 inch	Joint Efficiency, per cent	Welding Speed, fpm	Power Setting[a], volts	Preset Upset Distance, mils	Upset Force, lb	Vee Width, mils	Contact Tip to Squeeze Roll Centerline Distance, inches	Contact to Strip Edge Distance, mils
				AA2014-T6 Aluminum Alloy, 0.068 Inch Thick							
FJ 1389	61.2	46.6	2.5	87	160	380 (Y)	338	--	120	1.7	45
				AA7179-T6 Aluminum Alloy, 0.062 Inch Thick							
FJ 1451	60.3	53.9	2.0	76	160	340 (Y)	186	--	110	1.7	45
				AISI 301 Full Hard Stainless Steel, 0.072 Inch Thick							
FJ 712	166.2	117.7	2.0	87	250	485 (Y)	--	6000	110	1.7	30
				AISI 310 Full Hard Stainless Steel, 0.072 Inch Thick							
FJ 1001	127.1	92.5	2.0	93	250	510 (Y)	--	6000	110	1.7	30
				AISI 310 Full Hard Stainless Steel, 0.114 Inch Thick							
FJ 617	122.0	104.0	2.5	89	180	405 (D)	--	6750	170	3.0	215
				Ti-6Al-4V Alloy, 0.063 Inch Thick							
FJ 1602	137.3	94.0	15.5	100	160	350 (Y)	189	--	150	1.7	15

(a) (Y) indicates a low power range.
(b) (D) indicates a high power range.

Also, welding studies were conducted with one thickness of each of the aluminum alloys. As described in the Phase I section of this report, the 2014-T6 and 7179-T6 alloy strips were welded and high strengths were obtained. These alloys are weldable with the high-frequency process within a narrow range of welding conditions. Additional studies are needed to establish whether cracking in the weld upset is of concern. Welding studies also were conducted with the 5456-H343 alloy, but the welds were very weak. The welding studies with the 5456-H343 aluminum alloy were conducted using a guiding arrangement different from the other alloys; with the guiding arrangement that was used, the alloy showed poor weldability. However, the alloy should be studied with the same guiding arrangement as the other alloys before a final judgment can be made concerning its weldability.

For the type of vee formed in these studies, the primary effect of increasing the material thickness is to increase the difference in separation between the top and bottom edges of the strips. Whenever there is a difference in separation between the strip edges, the proximity effect causes the nearer edges to heat more than the edges which are further apart. Phase I studies showed that some latent heat is required to prevent cooling below welding temperatures between the vee apex and the squeeze-roll centerline. The total upset does not occur until the strips reach the squeeze-roll centerline, but no further heating occurs between the vee apex and the squeeze-roll centerline. To obtain a uniform weld, the edges of the strips must contain enough latent heat to prevent excessive cooling during the travel time between the vee apex and the squeeze-roll centerline. While heating the top edges to the proper welding temperature, the current density increases at the nearer bottom edges due to the proximity effect and this will cause excess molten material at the bottom of the weld. Evidence of overheating at the bottom of the weld was found in Phase I studies. Comparison of the welds made in 0.072- and 0.114-inch-thick AISI 310 stainless steel shows more cast metal at the bottom of the thicker material. To obtain the same upset pressure at the weld plane, the upsetting force must be increased as the thickness increases. A weld made using 6750 pounds of upset force for 0.114-inch-thick stock, had less upset than a weld which was made with 6000 pounds of upset force in 0.072-inch-thick material.

The joint efficiencies of Welds FJ 617 and FJ 1001, made in 0.114- and 0.072-inch-thick strips, respectively, were approximately equal. Examination of transverse metallographic sections of these two welds showed that the weld in 0.072-inch thick strips had a much narrower heat-affected zone than the weld in the 0.114-in.-thick strips. The narrower heat-affected zone was attributed to a faster welding speed, a reduced contact-to-squeeze-roll distance, and only 40 per cent of the heating time required to weld the thicker material. Welds in the thinner strips were made with upsetting forces of larger unit intensity than the welds in the thicker strips. Since the maximum joint efficiencies of the 0.072- and 0.114-inch-thick weldments were about equal (93 and 89 per cent, respectively) thickness did not have an appreciable effect on weld strength.

The force required for twisting flat strips varies with the cube of the stock thickness and thus very sturdy equipment is required for welding thick strips. Alignment of the abutting edges becomes increasingly important when thickness is reduced. The guiding and aligning equipment, therefore, must be capable of maintaining the edge alignment within the required limits.

TABLE II-3. MATERIAL THICKNESSES REQUIRED FOR SUPPORTING 4000 LB MINIMUM AND 16,000 LB MAXIMUM LOAD PER INCH OF JOINT LENGTH[a]

Material	Required Load, lb	Yield Strength of Weldment, ksi	Thickness Required[b], in.
AA2014-T6	4,000	46.6	0.086
	16,000		0.340
AA5456-H343	--	--	--
AA7179-T6	4,000	53.9	0.075
	16,000		0.300
AISI 301 (full hard)	4,000	117.7	0.034
	16,000		0.136
AISI 310 (full hard)	4,000	104.0	0.038
	16,000		0.154
Ti-6Al-4V	4,000	94.0	0.043
	16,000		0.170

(a) Calculations are based on the yield strength of welds having the greatest joint efficiency.

(b) $\text{Thickness} = \frac{\text{required load per inch of joint length}}{\text{yield strength of the weldment}}$.

Information also was obtained during Phase I to establish required thicknesses for supporting 4000 lb minimum and 16,000 lb maximum load per inch of joint length. The thicknesses calculated to support the required loads on the basis of earlier strength-test results* are reported in Table II-3. It is likely that the material thickness can be reduced when welding conditions that will produce optimum yield strength are developed.

*Reported in Table II-2.

PHASE III

Evaluate the information from Phases I and II and project this information into design of tooling configurations as required for the establishments of final tooling parameters for a production system utilizing this process for the manufacturing of space-vehicle components. The final equipment must be capable of utilization on large-diameter (over 300 in.) structures or demonstrate some other unique capability justifying the necessary expenditure funds for production installation. Adaptability of basic equipment to a range of materials, sizes, and configurations will be a critical factor.

PHASE III. PRODUCTION SYSTEM

Phase III of the research program was aimed at evaluating information obtained from Phases I and II and projecting this information into tooling-design configurations. These configurations were required to establish final tooling parameters for a space-vehicle components production-manufacturing system utilizing the high-frequency welding process. Criteria for the final tooling design included the following:

(1) The final equipment must be capable of utilization on large diameter (over 300 inch) structures or demonstrate some other unique capability justifying the necessary expenditure of funds for production installation.

(2) The basic equipment should be adaptable to a range of materials, sizes, and configurations.

On the basis of work completed during this program, tooling requirements were established for welding strips. These requirements are important in extending the process to other materials, large-diameter cylinders, and special configurations in which NASA is interested.

The major purpose of tooling for high-frequency resistance welding is to form the vee and control its configuration during welding. Another important purpose of the tooling is to forge the parts together at the proper time and temperature and to control the stresses developed in the weld area until the danger from cracking at elevated temperatures no longer exists. Tooling also performs additional important functions. The tooling feeds the material through the welding station, guides the edges to form the vee, and aligns the edges for welding. In many applications, the tooling is used to form the materials to the desired shape. Therefore, many of the process variables are controlled through the tooling that is used with the process.

The most important factor in determining tooling requirements for high-frequency resistance welding is the ability to form and control the vee between the two edges to be welded. As described earlier in this report, the configuration of the vee has very important effects on the current and heat distribution obtained about the edges being advanced through the welding station. To provide proper heating for welding, <u>the vee must be formed properly</u> and <u>the configuration of the vee must be controlled during welding</u>. To establish proper configuration of the vee, the following characteristics of the parts being welded are important:

(1) Material

(2) Material properties

(3) Configuration of the parts.

The material to be welded has various effects on the operation of the high-frequency resistance welding process. Although the process is adaptable to welding a wide variety of metals, welding conditions may be so different that the tooling or fixturing requires modification. For example, in the program just completed, the original tooling was satisfactory for welding low-carbon steel but significant modifications to the tooling were required to obtain conditions for welding the aluminum alloys.

Tooling modifications were required to provide a strip separation sufficient to eliminate arcing across the vee. When aluminum alloys were welded with the strip separation used for steel, arcing occurred across the vee and inconsistent weld quality was obtained.

The properties of the materials to be welded also influence tooling requirements. Yield strength of the materials was of special importance in the present program to establish whether guiding the strips was done with elastic or plastic deformation. With some of the materials used in the program, some upsetting occurred along the outbound edges of the strips as these edges passed through the squeeze rolls. Modulus of elasticity of the materials also was important to establish the strip separation and the forces required to obtain the desired strip separations.

The configuration of the parts involved in welding with the high-frequency resistance-welding process also will influence tooling designs. The shape, size, and position of the parts need to be considered. Although satisfactory tooling has been developed for making tubing and pipe and welding of strips, it appears that special tooling will be needed for welding large-diameter cylinders, joining large flat sheets, and for welding large-size products. Consideration should be given for example to advantages of moving the welding head rather than moving the product. Special configurations such as tees, H-sections, and I-sections probably can be fabricated with existing equipment although some modifications would be required to accommodate each of these special shapes.

STUDIES OF TOOLING

During the present program, information was obtained pertaining to requirements of the vee, methods for forming the vee, and methods for controlling the vee. This information was developed throughout the program when required to provide special tooling for welding the various materials that were included in the program.

Early in the program welding studies showed the configuration and behavior of the vee during welding had significant effects on welding results and on the behavior of the process during welding. To establish the important effects and to establish control of the vee, several guiding methods for forming the vee were investigated. Then on the basis of these studies, one of the guiding methods was selected for use with the remaining program materials.

Studies were conducted to establish the limiting condition of various methods for forming the vee and to use these limiting conditions to determine the vee requirements for welding. Several methods for forming the vee were studied by means of laboratory experiments while other methods either were not feasible or could not be evaluated in the laboratory. Laboratory studies were made of the following methods for forming the vee:

(1) Twisting and elevating each strip upstream from the squeeze point

(2) Combination of twisting, forcibly separating, and elevating each strip upstream from the squeeze point

(3) Forcible separation of strips in the flat position

(4) Dual elevation combined with forcible separation of the strips

(5) Prebent strips.

Two additional methods for forming the vee were considered:

(1) Tube forming

(2) Quarter-formed strip.

These latter methods were not considered useful to the program because of the additional equipment and material cost and because of the difficulties expected in forming the tubing or quarter rounds from the high-strength materials in the program. The methods for forming the vee for welding are discussed in the following sections.

Twisting and Elevating

The characteristics of a vee formed by twisting and elevating are similar to the characteristics of a vee formed only by twisting. Therefore, the following discussion applies also to strips which are not elevated before radially twisting. The calculated strip separations obtained by twisting 0.090-inch-thick strips through a series of angles using the lower outboard corner as the hinge point for rotation are shown in Figure III-1. Strips which entered the welding station with the lower outboard edge at the same level as the squeeze rolls gave less trouble with buckling when these strips were elevated upstream from the primary guide. Strips which entered the weld station with the lower outboard edge higher than the squeeze rolls required less radial angle at the primary guide to form the same vee opening. The radial angle under the contacts was the same whether the outboard edge was elevated or level.

Most of the welds made in this program employed a vee formed by twisting the strips and elevating them upstream from the slide guide. The advantages and uses for this method of forming the vee are listed below:

(1) A vee suitable for welding can be formed in materials with high strength and low ductility.

(2) A wide strip separation can be obtained for alloys which require a wide vee.

(3) The strip separation was adjustable to prevent arcing.

(4) With proper care and adjustment the inboard edges are not damaged before welding.

(5) The edges of the strips are parallel at the weld point.

(6) Long lengths are readily welded.

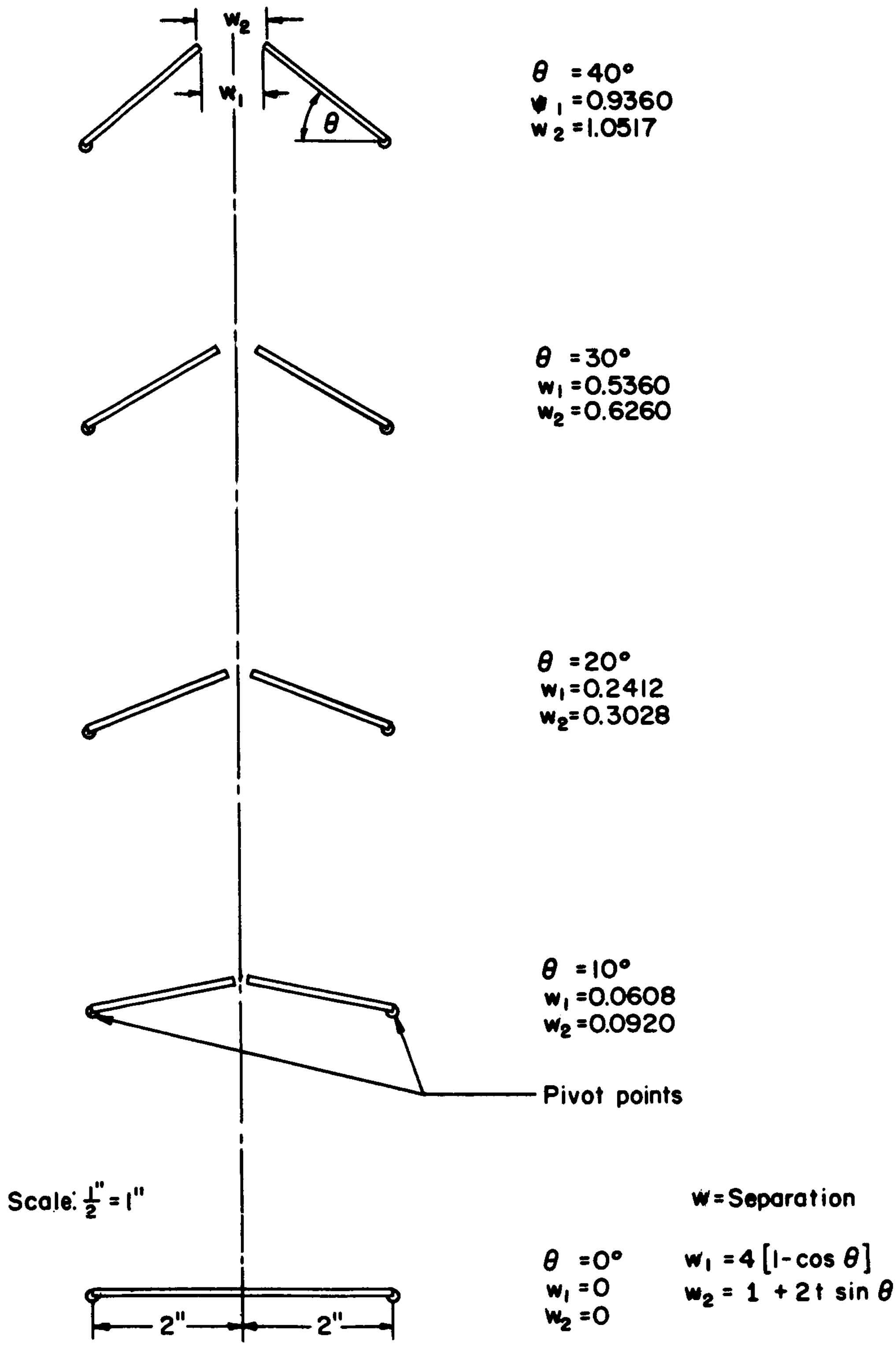


FIGURE III-1. SEPARATION BETWEEN 0.090 BY 2-IN. STRIPS AS THEY ARE ROTATED FROM 0 TO 40 DEGREES IN 10-DEGREE INCREMENTS AROUND THE LOWER OUTER CORNER

The following are the limitations to this method of forming the vee:

(1) Some of the squeeze roll force is used to overcome the friction forces existing on the top aligning roll.

(2) The bottom edges are closer together than the top edges as was shown in Figure III-1, and the current density on the bottom edges is greater because of the proximity effect. The difference in separation between the top and bottom edges increases as the strip thickness increases and when the angle of twist increases.

(3) The strips may be plastically deformed, depending on the vee opening required, and the modulus and yield strength of the material. Plastic deformation of the strips can cause residual stresses in the welds.

Twisting, Forcibly Separating, and Elevating

When twisted strips approach the squeeze point from an elevation higher than the squeeze point, the separation between the strips increases. The advantages and applicability of this method of forming the vee are listed below:

(1) Materials with little ductility and a high yield strength may be used to form a vee with this method.

(2) The separation between the strips and the radial angle of the strips may be readily changed over a wide range.

(3) The squeeze-roll force is used directly to upset the weld.

(4) With proper care the inboard edges of the strips are not damaged in forming the vee.

(5) Very little plastic deformation of the strips occurs for most materials.

(6) Long lengths are readily welded.

The chief limitation to this method is that the proximity effect causes the bottom edges of the strips to heat to a greater extent than the top edges of the strips. This effect is especially pronounced for thick materials which are welded with this method of forming the vee. This difference in heating between the top and bottom of the weld causes differences in the amount of weld reinforcement on the top and bottom of the weld.

This method of forming the vee was applicable to mild steel and stainless steel, but aluminum alloys, which require a wide strip separation, were found to buckle excessively.

Forcible Separation - Flat Position

The strip separation that was expected with elastic bending of flat strips was calculated assuming that the strips behaved as a cantilever beam. With strips in the flat position, the deflection of the strips at various distances from the vee apex using a slide guide 25.81 inches from the vee apex was calculated from the beam formula, as described in Appendix B. Strip-separation measurements obtained with strips threaded through the mill are compared with calculated values for elastic bending in Figure III-2. The measured values of separation were greater than the calculated values. This behavior was attributed to plastic deformation of the strips and a downstream shift in the apex of the vee. The curves also show that the legs of the vee are curved. Because of this curvature, the term "longitudinal angle" should be used with caution to describe the vee.

The studies also showed that with strips in the flat position the needed strip separation could not be obtained by elastic bending alone. Strip separations that were satisfactory for welding mild steel strips in the flat position were achieved with plastic deformation of the strips. With the aluminum and stainless steel alloys, satisfactory strip separations could not be achieved in the flat position.

The advantages and applications for the flat method of forming the vee are given below:

(1) The tooling required to form a vee from forcibly separated strips is relatively simple.

(2) The strip edges enter the weld station in a parallel position and the edges are butted together uniformly.

(3) The inboard edges of the strips are not damaged provided the guides used to separate the strips are positioned far enough upstream so that the force acting on the inboard strip edges is relatively small.

The limiting conditions for this method of forming the vee are given below:

(1) This method is applicable to easy-to-form materials, especially materials with a low yield strength.

(2) The shape of the vee may be readily changed, but the opening of the vee is limited by the yield strength of the material. A vee wide enough for welding without arcing could not be formed in the high-yield-strength materials used in this program.

(3) Much of the squeeze force was used to deform and position the strips.

(4) Since the strip separation depends on the yield strength of the material, part of the vee opening is a result of plastic deformation. Weldments made from plastically deformed strips contained residual tensile stresses.

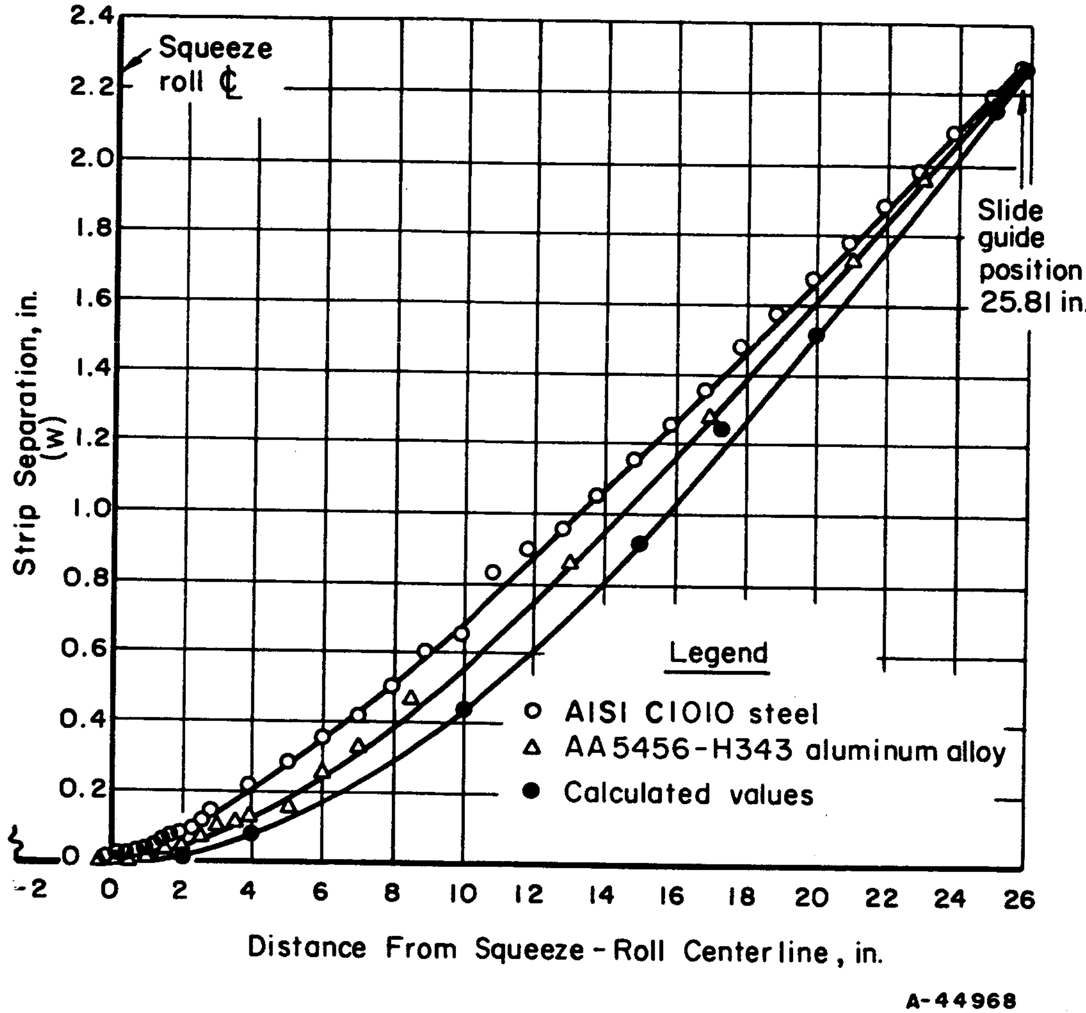


FIGURE III-2. RELATIONSHIP OF STRIP SEPARATION AND DISTANCE FROM THE SQUEEZE ROLLS WITH STRIPS IN THE FLAT POSITION

Dual Elevation - Forcible Separation

With this method the vee was formed by guiding one strip into the weld station from an elevation higher than the other strip, then the strips were forcibly separated. A modification to this method of forming the vee includes twisting one or both of the strips. The vee is formed in the vertical and in the horizontal planes. This method for forming the vee may be applied with the following advantages:

(1) This method may be used on most materials, including difficult-to-form materials.

(2) The tooling for this method of forming the vee is relatively simple.

(3) The force applied by the squeeze rolls is used directly in upsetting the welds.

(4) Thick materials may be welded by this process.

(5) The inboard edges of the strips are not damaged in forming the vee.

(6) Since the strip section modulus is at a minimum when the strips are bent in the vertical direction, the strips will not usually be plastically deformed. For thick sections, the stress in the material must be calculated to insure that the material is not being plastically deformed.

(7) Long lengths are readily welded with this method of forming the vee.

The following limitations apply to this method of forming the vee:

(1) The proximity effect causes the lower inside edge of the upper strip and the upper inside edge of the lower strip to heat more than the other parts of the strips. This method of forming the vee is thus better suited to materials such as steel which can be welded by the high-frequency process over a wide range of welding power.

(2) The edges of the strips are brought together with a wiping or shearing action instead of butting directly together.

Prebent Strips

It is possible to form a vee by prebending the strips to a predetermined radius as shown in Figure III-3. This method for forming a vee has the following applications and advantages:

(1) This method of forming the vee is best suited for easy-to-form materials and materials with a low yield strength.

(2) A variety of vee configurations could be formed and studied by using various strip radii.

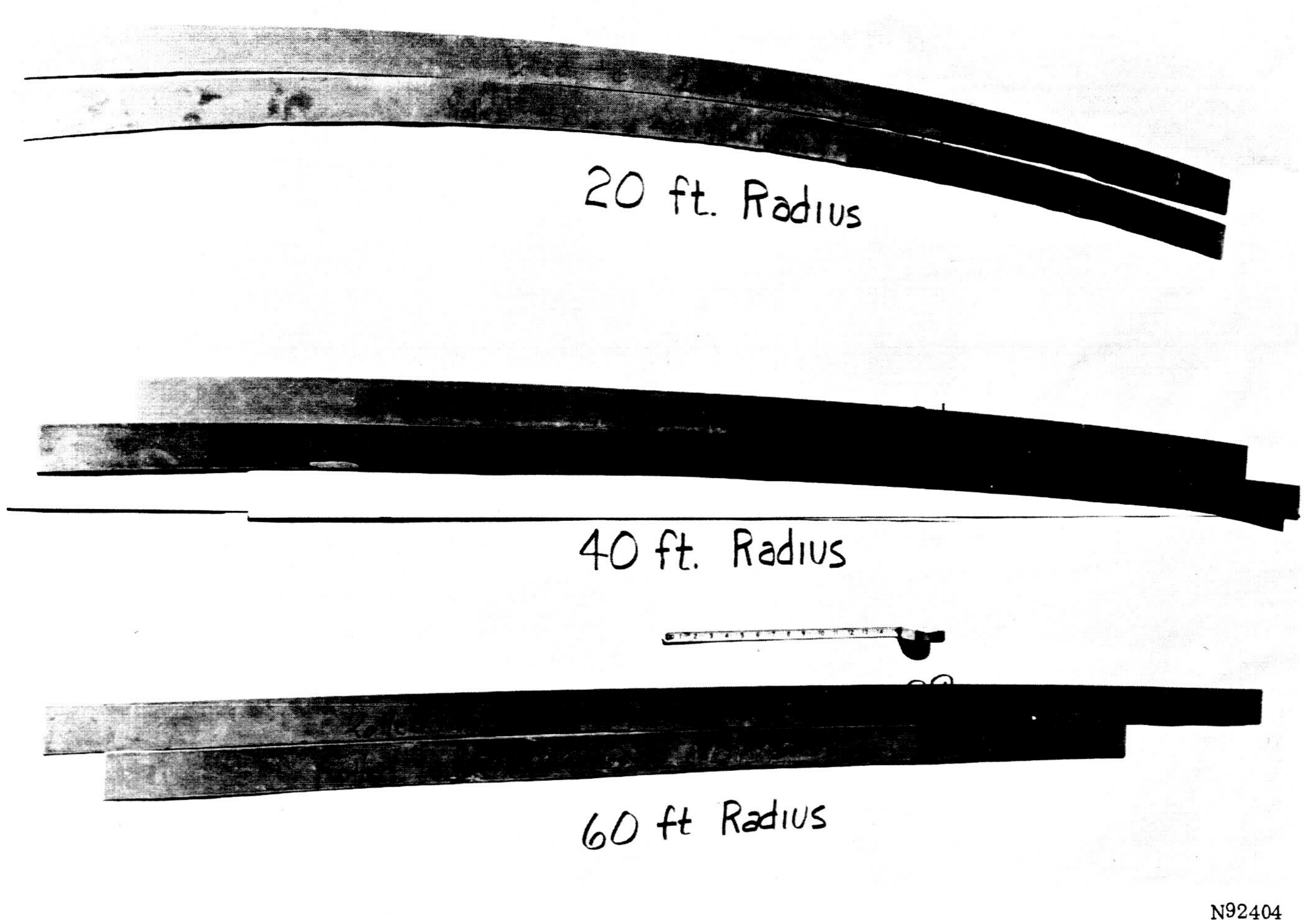


FIGURE III-3. APPEARANCE AND COMPARISON OF 2-INCH-WIDE AISI C1010 STEEL STRIPS PREBENT BY THREE-POINT ROLL BENDING TO 20, 40, AND 60-FT RADII

(3) Squeeze rolls do not have to supply any force to control the vee or to form the strip, and all the squeeze force supplied is used directly to upset the weld.

(4) This type of vee is suitable for thick materials where it is difficult to form the vee by other methods.

(5) The edges are heated and butted together uniformly.

(6) The edges of the strips in the vee are parallel and no difficulty is encountered with overheating the narrow edges by the proximity effect. For thick strips and for materials with a narrow power range suitable for welding, the edges should remain as parallel as possible.

The following are the limiting conditions for using prebent strips to form the vee:

(1) The material must have sufficient ductility to permit the prebending operation.

(2) The prebending operation leads to distortion of the edges to be welded. In some cases, the prebending operation causes excess wrinkling of the entire strip.

(3) The prebent strips did not readily straighten out after leaving the welding station. Welds made from prebent strip contain residual tensile stresses which may damage the weld.

(4) The prebent strip was not readily applicable to long lengths.

This method of forming the vee could be used for some of the materials used in this investigation, but an extra operation was required in preforming the strips, and no direct application was visualized for space launch vehicles.

Vee Formed in Tubing

Welded tubing is a common application of the high-frequency resistance welding process. Tubing was unsatisfactory for this investigation because the materials being investigated would be difficult to form into tubing. The shape of tubing also makes it difficult to evaluate the mechanical properties of welds. The advantages and the applications of using tubing to form the vee are given below:

(1) The shape of the vee may be readily changed, and it is possible to obtain a wide vee for materials which require a large strip separation.

(2) The squeeze-roll force is used directly in upsetting the weld and none of the squeeze-roll force is required to overcome friction or to help form the vee.

(3) A wide variety of materials may be welded by this method.

(4) The opposed edges of the strips at the vee can be made parallel and prevent any overheating of one area of the edge by the proximity effect.

(5) The inboard edges of the strips are not damaged while welding.

(6) Long lengths are readily welded.

The following are the limiting conditions for using tubing to form the vee:

(1) The cost of the equipment to form the tubing is expensive.

(2) The materials being studied for space-launch-vehicle applications are very difficult to form into tubing.

Quarter-Formed Strip

Quarter-forming is a term used to describe strip formed into quarter-round sections, that is, the upper half of a transverse section of tubing. This method of forming the vee was unsatisfactory for the same reasons given above for tubing. The advantages and uses of this method are the same as given above for tubing.

TOOLING DESIGN CONCEPTS

Tooling design concepts for fabricating configurations of special interest to NASA were developed. In present and future space-launch vehicles, stiffened tank structures utilizing tee-shaped stiffeners are being considered. The high-frequency welding process is expected to be useful in two areas of fabricating the tee-stiffened tankage.

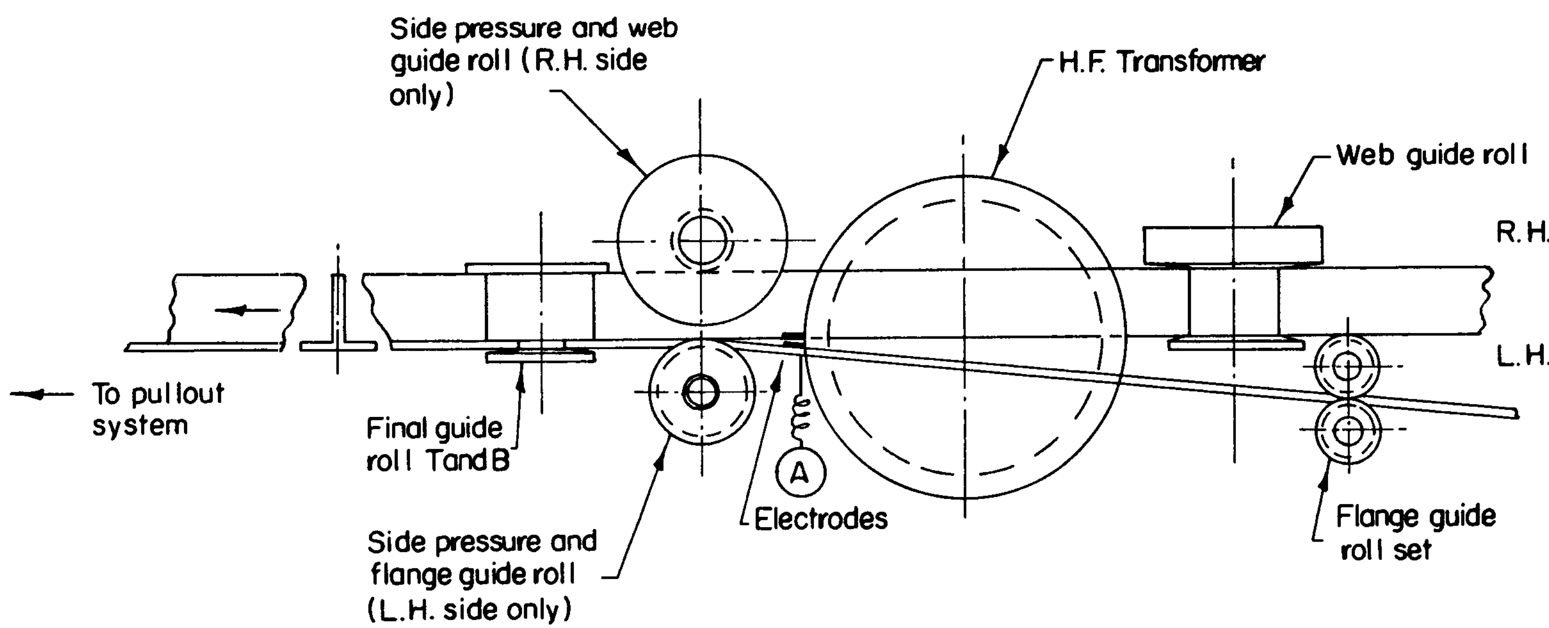
(1) Fabricating the tee sections

(2) Attaching the tees to the tank wall.

For fabricating tee sections, one preliminary concept for guiding the components through the welding station is illustrated in Figure III-4. The tooling required for guiding the strip properly is expected to be less complex than the tooling used in past studies for making butt welds in strip.

A preliminary layout drawing of the tee tooling and guide system was made to help establish future requirements for the tooling. Based on this design concept, the tooling required for guiding the strips appears simple.

Additional information is needed to establish the final method for transferring the high-frequency current into the strips and establish that proper current and heat distribution is achieved for making the welds. Section views of the tees as they pass through the welding station are shown in Figure III-5. The tooling required for guiding the tees through the welding station will be determined by the orientation of the tee



(A) Contact pressure to be developed with air, hydraulic or spring loading system to push flange against side contact. Mounting shoe on L.H. side must be modified.

0-27801

FIGURE III-4. CONCEPT FOR EXPERIMENTAL MILL FOR MAKING TEE JOINTS WITH HIGH-FREQUENCY RESISTANCE WELDING (TOP VIEW)

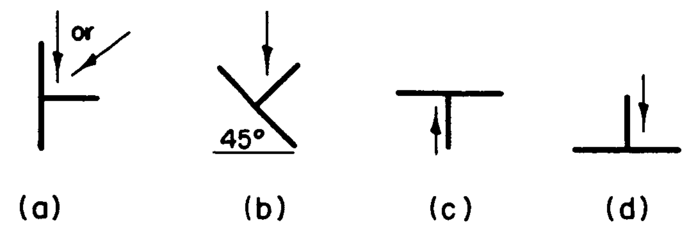


FIGURE III-5. POSSIBLE ORIENTATION OF TEE CROSS SECTIONS AT THE HIGH-FREQUENCY WELDING STATION

Arrows show direction of welding head motion.

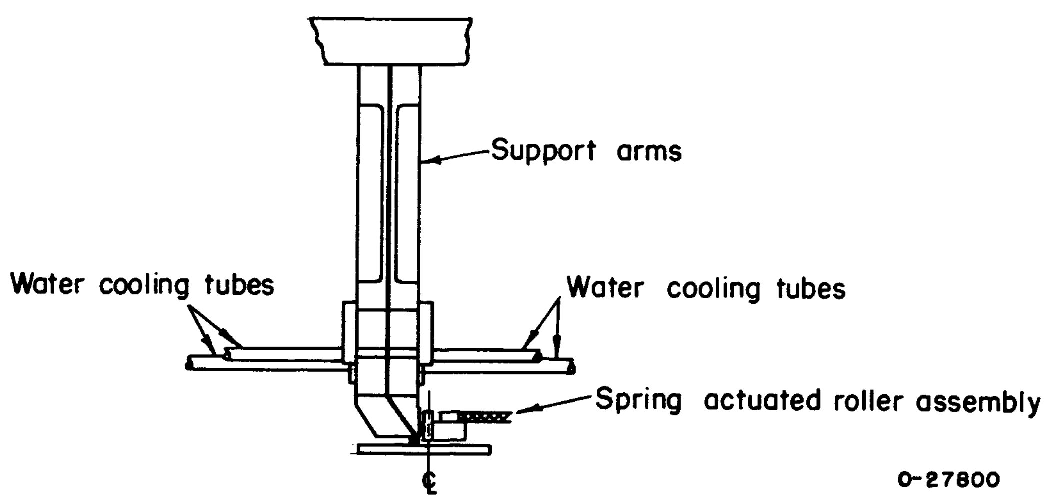


FIGURE III-6. DESIGN CONCEPT FOR SLIDING-CONTACT-SHOE ARRANGEMENT FOR FABRICATING TEES cross section at the welding station. One preliminary design concept for the sliding-contact-shoe arrangement for welding tees is shown in Figure III-6. Studies will be needed in the future to obtain additional information on the tooling, guiding, and current transfer methods for fabricating the tees.

A similar tooling concept would be useful in making the tee-section-to-plate weld. Figure III-7 shows a section through a plate fabricated in this manner. Similar plates are currently being machined from solid aluminum alloy plates for use in launch-vehicle structures. Fabrication of this plate by high-frequency resistance welding would reduce the unit cost significantly.

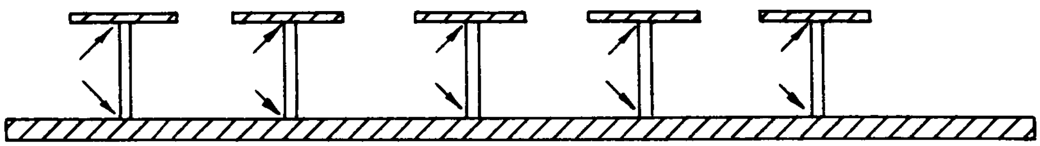


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FIGURE III-7. SECTION OF SKIN PANEL SHOWING PROPOSED USE OF HIGH-FREQUENCY RESISTANCE WELDING

* * * * * * *

The research described in this report was conducted during the period from June 10, 1962, to June 10, 1963. Data obtained during the research are recorded on pp 1-100 in Record Books Nos. 18721, 19596, 19735, 19962, 20178, and pp 1-66, Record Book No. 19419.

Conduct of this research involved the use of a Thermatool VT 280 welding apparatus and the use of a licensed welding process owned by the Thermatool Corporation. This process can be licensed from the Thermatool Corporation.

APPENDIX A

TABULATED DATA

TABLE A-1. SUMMARY OF THE WELDING CONDITIONS AND WELDING RESULTS FOR SATISFACTORY WELDS IN 0.068-INCH-THICK AA2014-T6 ALUMINUM ALLOY[a]

Weld No.	Power Setting[b], volts	Preset Upset Distance, mils	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Backup Force at Squeeze Rolls, lb	Arcing Observed at the Vee[c]	Contact to Edge Distance[d], mils	Tensile Strength[e], ksi	Yield Strength (0.2% Offset), ksi	Elongation[f], per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture	Remarks
Evaluations of Power and Upset Distance at 90 Ft/Min Using a Narrow Vee													
FJ 1329	335 (Y)	136	90	125	3750	Yes	COE	31.9/41.3	–	*	45/59	Weld	–
FJ 1332	335 (Y)	136	90	125	3750	Yes	20	55.2/–	–	*	79/–	Weld	–
FJ 1333	320 (Y)	170	90	125	3750	Occ.	20	54.2/46.6	–	*	77/66	Weld	–
FJ 1335	335 (Y)	170	90	125	3750	Occ.	20	59.1/46.5	–	*	84/66	Weld	–
Evaluations of Power and Upset at 90 Ft/Min Using a Wide Vee													
FJ 1337	335 (Y)	170	90	160	3750	No	COE	47.6/50.0	–	*	68/71	Weld	–
FJ 1339	340 (Y)	136	90	160	3750	No	25	42.1/26.0	–	*	60/37	Weld	–
FJ 1340	350 (Y)	136	90	160	3750	No	25	43.8/32.2	–	*	59/46	Weld	–
FJ 1342	340 (Y)	170	90	160	3750	No	25	43.0/41.7	–	*	61/59	Weld	–
FJ 1343	350 (Y)	170	90	160	3750	No	25	34.8/29.3	–	*	50/42	Weld	–
FJ 1344	360 (Y)	170	90	160	3750	No	25	42.7/42.9	–	*	61/61	Weld	–
FJ 1345	340 (Y)	204	90	160	3750	No	25	55.5/54.3	–	*	79/78	Weld	–
FJ 1346	330 (Y)	204	90	160	3750	No	25	54.5/54.2	–	*	78/77	Weld	–
FJ 1348	320 (Y)	204	90	160	3750	No	25	56.3/50.0	–	*	80/71	Weld	–
Evaluations of Power and Upset at an Increased Speed													
FJ 1349	430 (Y)	204	160	160	3750	No	25	34.0/48.3	–	*	48/69	Weld	Overheated
FJ 1350	420 (Y)	204	160	160	3750	No	25	39.0/36.2	–	*	56/52	Weld	Overheated
FJ 1351	410 (Y)	204	160	160	3750	No	25	55.0/56.5	–	*	78/81	Weld	–
FJ 1352	400 (Y)	204	160	160	3750	No	25	57.0/55.5	–	*	81/79	Weld	–
FJ 1353	390 (Y)	204	160	160	3750	No	25	53.0/58.9	–	*	76/84	Weld	–
FJ 1354	410 (Y)	170	160	160	3750	No	25	51.5/–	–	*	73/–	Weld	–
FJ 1355	400 (Y)	170	160	160	3750	No	25	48.9/50.0	–	*	70/71	Weld	–
FJ 1356	420 (Y)	170	160	160	3750	No	25	51.5/46.3	–	*	73/66	Weld	–
FJ 1357	420 (Y)	134	160	160	3750	No	25	48.9/46.7	–	*	70/67	Weld	–
FJ 1358	430 (Y)	134	160	160	3750	No	25	40.9/39.1	–	*	58/56	Weld	–
FJ 1359	440 (Y)	134	160	160	3750	No	25	48.3/31.6	–	*	69/45	Weld	–
FJ 1367	410 (Y)	170	160	160	3750	No	25	53.8/44.8	49.0	*	77/64	Weld	Repeat of Weld FJ 1354
FJ 1371	390 (Y)	238	160	120	4500	No	45	54.7/57.4	–	–	78/82	Weld	–
FJ 1372	400 (Y)	238	160	120	4500	No	45	59.6/55.4	57.8/47.0	2	85/79	Weld	–
FJ 1373	410 (Y)	238	160	120	4500	No	45	44.6/42.5	–	1.5	64/61	Weld	Overheated
FJ 1389	380 (Y)	238	160	120	4500	Yes	45	61.2/–	46.6	2.5	87/–	Weld	
Evaluations of Power and a Constant Upset Force													
FJ 1362	410 (Y)	–	160	155	2400	No	27	49.0/–	–	*	70/–	Weld	–
FJ 1363	400 (Y)	–	160	155	3000	No	27	46.1/46.1	–	*	66/66	Weld	–
FJ 1364	410 (Y)	–	160	155	3000	No	27	43.1/43.5	–	*	61/62	Weld	–
FJ 1368	390 (Y)	–	160	155	3750	No	27	46.1/56.4	49.8	1.5/2.0	66/80	Weld	–
Evaluations of Power and Upset Distance at 360 Ft/Min													
FJ 1375	550 (Y)	204	360	140	4500	No	35	55.3/56.3	49.6	2.0/1.5	79/80	Weld	–
FJ 1378	560 (Y)	204	360	140	3750	No	35	55.2/53.0	52.1	1.0/1.5	79/76	Weld	–
FJ 1381	520 (Y)	238	360	175	4125	Occ.	43	48.2/59.6	52.7	1.5/2.0	69/85	Weld	–
FJ 1384	530 (Y)	238	360	175	4125	Occ.	43	53.0/58.9	52.6/49.4	1.5/2.0	76/84	Weld	–
Evaluations of Conditions of FJ 1371 at 180 Ft/Min													
FJ 1387	390 (Y)	238	180	120	4125	No	45	52.6/58.1	51.7	1.5/2.0	75/83	Weld	–
Evaluations of a Larger Contact-to-Strip Edge Distance Holding the Other Conditions of FJ 1371, FJ 1372, and FJ 1373 Constant													
FJ 1390	390 (Y)	238	160	130	4125	No	100	59.5/–	46.9	2.0	85/–	Weld	–
FJ 1391	400 (Y)	238	160	130	4125	No	100	53.6/50.6	46.7/46.6	1.5/1.5	76/72	Weld	–
FJ 1392	410 (Y)	238	160	130	4125	No	100	57.6/36.5	49.6	2.0/*	82/52	Weld	–
Evaluations of Welding Without Applying Mill Coolant to the Contact Shoes, Holding the Other Conditions of Weld FJ 1392 Constant													
FJ 1393	410 (Y)	238	160	130	4125	No	100	56.0/50.7	45.1/44.5	1.5/1.5	80/72	Weld	–
Evaluations of Welding With Unequal Contact to Strip Edge Distance Between the East and the West Strip. Holding the Other Conditions of Weld FJ 1393 Constant													
FJ 1394	410 (Y)	238	160	130	4125	No	–	–	–	–	–	–	No weld; the contact to edge distance was 0.250 in. at the east strip and 0.000 in. at the west strip
Evaluations of Increasing the Contact Tip to Squeeze-Roll Centerline Distance to 2.55 In. (1-1/2 x 1.7 In.)													
FJ 1395	425 (Y)	204	160	276	4125	No	50	58.3/52.8	45.6/47.0	1.5/2.0	83/75	Weld	The vee was 0.130 in. wide at 1.7 in. from the squeeze roll centerline

Note: Footnotes on following page.

Footnotes for Table A-1.

(a) Conditions held constant except as noted in the table:

Angle of twist at guides – 45 deg
Angle of twist at contacts – 17 deg
Elevation at primary guides – 0 inches
Distance between squeeze-roll centerline and contacts – 1.7 inches
Contact shoe material – Mallory Elkaloy A
Contact shoe width – 3/8 inch
Contact shoe cooling – Water-soluble oil (except as noted)

(b) (Y) indicates a wye-to-wye transformer coupling (low power range); (D) indicates a delta-to-wye transformer coupling (high power range).

(c) Occ. = Occasional.

(d) COE = Contacts overlapped edges.

(e) Two strength tests for each weld.

(f) • Indicates less than 1 per cent elongation.

TABLE A-2. SUMMARY OF THE WELDING CONDITIONS AND WELDING RESULTS FOR WELDS IN AA 7179-T6 ALUMINUM ALLOY, 0.062 INCH THICK[a]

Weld No.	Power Setting[b], volts	Preset Upset Distance, mils	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Backup Force at Squeeze Rolls, lb	Arcing Observed at the Vee	Contact to Edge Distance, mils	Tensile Strength[c], ksi	Yield Strength (0.2% Offset), ksi	Elongation[d], per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture
						Evaluations of Power With a Medium Vee						
FJ 1402	350 (Y)	186	160	120	4125	No	40	43.4	43.2	1.0	54	Weld
								53.8	–	*	67	Weld
FJ 1403	340 (Y)	186	160	120	4125	No	40	57.1	52.4	2.0	69	Weld
								55.7	53.1	1.5	69	Weld
						Evaluations of Power With a Narrow Vee						
FJ 1407	330 (Y)	186	160	110	4125	No	45	(e)	(e)	(e)	(e)	(e)
								57.5	–	*	72	Weld
FJ 1408	340 (Y)	186	160	110	4125	No	45	60.3	53.9	2.0	76	Weld
								45.1	–	1.0	56	Weld
FJ 1409	345 (Y)	186	160	110	4125	No	45	53.6	53.3	1.0	67	Weld
								53.4	53.2	1.0	67	Weld

(a) Conditions held constant:

Angle of twist at guides	– 45 deg	Contact shoe material	– Mallory Elkaloy A
Angle of twist at contacts	– 17 deg	Contact shoe width	– 3/8 inch
Elevation of primary guide	– 0 inch	Contact cooling	– Water-soluble oil coolant
Contact to squeeze-roll centerline distance	– 1.7 inch		

(b) (Y) indicates a wye-to-wye transformer coupling (low power range).

(c) Two strength tests from each weld.

(d) * Represents less than 1 per cent elongation.

(e) Machined specimen was cracked; not evaluated.

TABLE A-3. SUMMARY OF THE WELDING CONDITIONS AND WELDING RESULTS FOR WELDS IN FULL HARD 0.114-INCH-THICK AISI 310 STAINLESS STEEL[a]

Weld No.	Power Setting,[b] volts	Preset Upset Distance mils	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Upset Force, lb	Arcing Observed at the Vee	Contact to Squeeze Roll Centerline Distance, inches	Contact to Edge Distance, mils	Tensile Strength,[c] ksi	Yield Strength, (0.2% Offset), ksi	Elongation, per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture[d]	Remarks
							Evaluation of Upset Force							
FJ 613	405 (D)	–	180	135	4500	Occ[e]	3.0	215	113.3	90.2	3	83	W	
									113.9	94.1	2.5	83	W	
FJ 617	405 (D)	–	180	135	6750	Occ.	3.0	215	122.0	104.0	2.5	89	W	
									113.4	97.4	3.0	83	W	
							Evaluation of Power at 97 mil Preset Upset							
FJ 619	360 (D)	97	90	145	6375	Yes	3.0	210	80.0	77.0	1.2	58	W	
									63.0	63.0	1.0	46	W	
FJ 620	325 (D)	97	90	145	6375	Yes	3.0	210	–	–	–	–	–	
									–	–	–	–	–	
FJ 621	515 (Y)	97	90	145	6375	Yes	3.0	210	–	–	–	–	–	
									–	–	–	–	–	
							Evaluation of Preset Upset Distance							
FJ 624	515 (Y)	137	90	145	6375	Yes	3.0	210	114.8	101.1	1.5	84	W	
									109.2	98.2	1.3	80	W	
FJ 623	515 (Y)	117	90	145	6375	Yes	3.0	210	–	–	–	–	–	
									–	–	–	–	–	
FJ 622	515 (Y)	97	90	145	6375	Yes	3.0	210	81.1	81.1	1.0	59	W	
									84.6	84.0	1.2	61	W	
FJ 625	330 (D)	37	90	145	6375	Yes	3.0	210	–	–	–	–	–	
									–	–	–	–	–	

TABLE A-3. (Continued)

Weld No.	Power Setting(b) volts	Preset Upset Distance mils	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Upset Force, lb	Arcing Observed at the Vee	Contact to Squeeze Roll Centerline Distance, inches	Contact to Edge Distance, mils	Tensile Strength,(c) ksi	Yield Strength, (0.2% Offset), ksi	Elongation, per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture(d)	Remarks
						Evaluation of Decreasing the Contact-to-Squeeze Roll Centerline Distance								
FJ 626	420 (Y)	97	90	85	6375	Yes	2.3	240	–	–	–	–	–	Underheated
									–	–	–	–	–	
FJ 627	490 (Y)	97	90	85	6375	Yes	2.3	240	112.5	103.6	1.0	82	W	
									117.4	97.4	1.0	86	W	
						Evaluation of Slow Speed Using the Reduced Contact-to-Squeeze Roll Centerline Distance								
FJ 628	350 (Y)	97	40	85	6375	Yes	2.3	240	99.2	78.8	1.5	72	W	
									99.8	81.3	1.3	73	W	
FJ 629	370 (Y)	97	40	85	6375	Very bad	2.3	240	–	–	–	–	–	
									–	–	–	–	–	
FJ 630	370 (Y)	97	40	85	6375	Very bad	2.3	240	101.8	82.8	2.0	74	W	Repeat of FJ 629
									96.9	75.7	2.8	70	W	

(a) Conditions held constant

Angle of twist at guides	- 30 deg	Contact shoe material	– Mallory Elkonite a-17
Angle of twist at contacts	- 15 deg	Contact shoe size	– 1/2 inch wide
Elevation at primary guide	- 0.39 inch	Contact cooling	– Water-soluble oil

(b) (Y) indicates a wye-to-wye transformer coupling (low power range);
(D) indicates a delta-to-wye transformer coupling (high power range).
(c) Two specimens were taken for each weld.
(d) W = Weld.
(e) Occ. = Occasional.

TABLE A-4. PRELIMINARY EVALUATIONS OF WELD STRENGTH IN 0.114-INCH-THICK AISI 310 STAINLESS STEEL

Specimens were made of 1/2 by 4 by 0.114-inch rectangular sections with the weld reinforcement removed.

Weld No.	Tensile Strength, ksi	Joint Efficiency, per cent
FJ 619	68.0	50
FJ 619	52.9	39
FJ 620	94.9	69
FJ 620	79.6	58
FJ 621	77.8	57
FJ 621	67.2	49
FJ 624	104.9	76
FJ 624	114.2	83
FJ 623	75.4	55
FJ 623	95.0	69
FJ 622	78.1	57
FJ 622	80.2	58
FJ 625	111.0	81
FJ 625	61.1	45
FJ 626	50.0	36
FJ 626	93.9	58
FJ 627	101.3	74
FJ 627	100.8	73
FJ 628	94.2	69
FJ 628	106.4	78
FJ 629	90.3	66
FJ 629	107.0	78
FJ 630	86.9	63
FJ 630	93.2	68

TABLE A-5. SUMMARY OF THE WELDING CONDITIONS AND WELDING RESULTS FOR WELDS IN 0.072-INCH-THICK AISI 310 FULL-HARD STAINLESS STEEL[a]

Weld No.	Power Setting,[b] volts	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Upset Force at Squeeze Rolls, lb	Arcing Observed at the Vee	Contact to Edge Distance, mils	Ultimate Tensile Strength,[c] ksi	Yield Strength (0.2% Offset), ksi	Elongation, per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture[d]
FJ 1001	510 (Y)	250	110	6000	No	30	125.8	98.1	2.0	85	W
							127.1	92.5	2.0	86	W
FJ 1002	525 (Y)	250	110	6000	No	30	125.8	110.0	1.0	85	W
							124.4	96.0	1.0	84	W

(a) Conditions held constant:

Angle of twist at guides	- 45 deg	Contact shoe material	– Mallory Elkaloy A
Angle of twist at contacts	- 15 deg	Contact shoe width	– 3/8 inch
Elevation at primary guides	- 0 inch	Contact shoe cooling	– None
Contact to squeeze-roll distance	- 1.7 inch		

(b) (Y) indicates a wye-to-wye transformer coupling (low power range).
(c) Two strength tests for each weld.
(d) W = weld.

TABLE A-6. SUMMARY OF THE WELDING CONDITIONS AND WELDING RESULTS FOR WELDS IN 0.072-INCH-THICK AISI 301 FULL-HARD STAINLESS STEEL[a]

Weld No.	Power Setting,[b] volts	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Upset Force at Squeeze Rolls, lb	Arching Observed at the Vee	Contact to Edge Distance, mils	Tensile Strength,[c] ksi	Yield Strength (0.2% Offset), ksi	Elongation, per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture	Remarks
						Evaluations of Power at 4125-lb Upset Force						
FJ 705	550 (Y)	250	110	4125	No	30	146.9	112.7	2.5	70	Weld	
							146.2	112.7	2.5	70	Weld	
FJ 707	540 (Y)	250	110	4125	No	30	143.4	111.7	2.5	69	Weld	
							148.4	112.6	2.5	71	Weld	
FJ 706	530 (Y)	250	110	4125	No	30	143.4	103.8	2.5	69	Weld	
							146.7	114.3	2.5	70	Weld	
						Evaluations of Power at 6000-lb Upset Force						
FJ 708	540 (Y)	250	110	6000	No	30	153.8	123.1	2.5	73	Weld	
							155.7	129.6	2.5	75	Weld	
FJ 709	525 (Y)	250	110	6000	No	30	151.1	133.9	2.0	72	Weld	
							159.0	128.0	2.5	76	Weld	
FJ 710	515 (Y)	250	110	6000	No	30	150.8	124.6	1.5	72	Weld	
							144.8	115.6	1.5	69	Weld	
FJ 711	500 (Y)	250	110	6000	No	30	160.7	125.4	2.5	77	Weld	
							160.7	125.0	2.5	77	Weld	
FJ 712	485 (Y)	250	110	6000	No	30	166.2	117.7	2.0	79	Weld	
							155.6	131.1	2.0	74	Weld	
						Evaluation at 7500-lb Upset Force						
FJ 713	485 (Y)	250	110	7500	No	30	–	–	–	–	–	This weld was not completely bonded

(a) Conditions held constant:

Angle of twist at guides	- 45 deg	Contact shoe material – Mallory Elkaloy A
Angle of twist at contacts	- 15 deg	Contact shoe width – 3/8 inch
Elevation of primary guides	- 0 inch	Contact shoe cooling – None
Contact tip-to-squeeze roll distance	- 1.7 inches	

(b) (Y) indicates a wye-to-wye transformer coupling (low power range).

(c) Two strength tests for each weld.

TABLE A-7. SUMMARY OF THE WELDING CONDITIONS AND WELDING RESULTS FOR WELDS IN 0.063-INCH-THICK TITANIUM-6 ALUMINUM-4 VANADIUM ALLOY[a]

Weld No.	Power Setting[b], volts	Preset Upset Distance, mils	Welding Speed, fpm	Average Vee Width at the Contacts, mils	Backup Force at Squeeze Rolls, lb	Arcing Observed at the Vee	Contact to Edge Distance, mils	Tensile Strength[c], ksi	Yield Strength (0.2% Offset), ksi	Elongation, per cent in 1 inch	Joint Efficiency, per cent	Location of Fracture[d]	Remarks
						Evaluations of Power at 0.189-Inch Preset Upset							
FJ 1602	350 (Y)	189	160	150	4125	No	15	136.7	83.8	14.0	100	UBM,HAZ,W	Fractured at 45 degrees through the weld
								137.3	94.0	15.5	100	UBM	
FJ 1603	360 (Y)	189	160	150	4125	No	15	140.0	124.5	13.0	100	UBM	–
								–	–	–	–	–	?
FJ 1604	370 (Y)	189	160	150	4125	No	15	Broke at the hole provided for the jaws of the testing machine					–
								–	–	–	–	–	–
						Evaluations of Increased Preset Upset							
FJ 1605	360 (Y)	205	160	150	4125	No	15	91.3	83.9	*(e)	68	W	–
								136.9	100.0	16.0	100	UBM	–
						Evaluations of Increased Speed							
FJ 1607	420 (Y)	205	250	150	4125	No	15	139.2	95.8	15.0	100	UBM	–
								–	–	–	–	–	–

(a) Conditions held constant:

Angle of twist at guides	– 45 deg
Angle of twist at contact tips	– 15 deg
Elevation at primary guides	– 0 inch
Contact-to-squeeze roll distance	– 1.7 inches
Contact shoe material	– Mallory Elkaloy A
Contact shoe width	– 3/8 inch
Contact shoe cooling	– None

(b) (Y) indicates a wye-to-wye transformer coupling (low power range).

(c) Two strength tests for each weld.

(d) UBM = unaffected base metal; HAZ = heat affected zone; W = weld.

(e) * Less than 1 per cent elongation.

APPENDIX B

EQUATIONS USED TO CALCULATE STRIP SEPARATION

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(1) $EI \frac{d^2y}{dx^2} = M = -Px$,

where E = Young's modulus

I = moment of inertia

y = deflection

M = moment

x = distance from the free end of the beam

P = force

(2) $I = \frac{bh^3}{12}$,

where b = length of the section

h = thickness of the section

(3) $EI \frac{dy}{dx} = -\frac{Px^2}{2} + C_1$

At $x = \ell$

$\frac{dy}{dx} = 0$, and

$C_1 = -\frac{P\ell^2}{2}$

(4) $EIy = -P\frac{x^3}{6} + P\ell\,\frac{2x}{2} + C_2$

At $x = \ell$ where ℓ = beam length

$y = 0$

$C_2 = \frac{P\ell^3}{3}$

(5) $EIy = -\frac{1}{6}Px^3 + \frac{1}{2}P\ell^2x - \frac{1}{3}P\ell^3$

Substituting ℓ - s for x where s = distance from the fixed end of the beam

(6) $$EIy = -\frac{P\ell s^2}{2} + \frac{Ps^3}{6}$$

(7) $$EIy_{max} = -\frac{P\ell^3}{3}$$

Equation (6) is the equation describing the elastic behavior of the inboard strip edges where the deflection, y, is one-half the vee width at any distance from the fixed end or apex of strips.